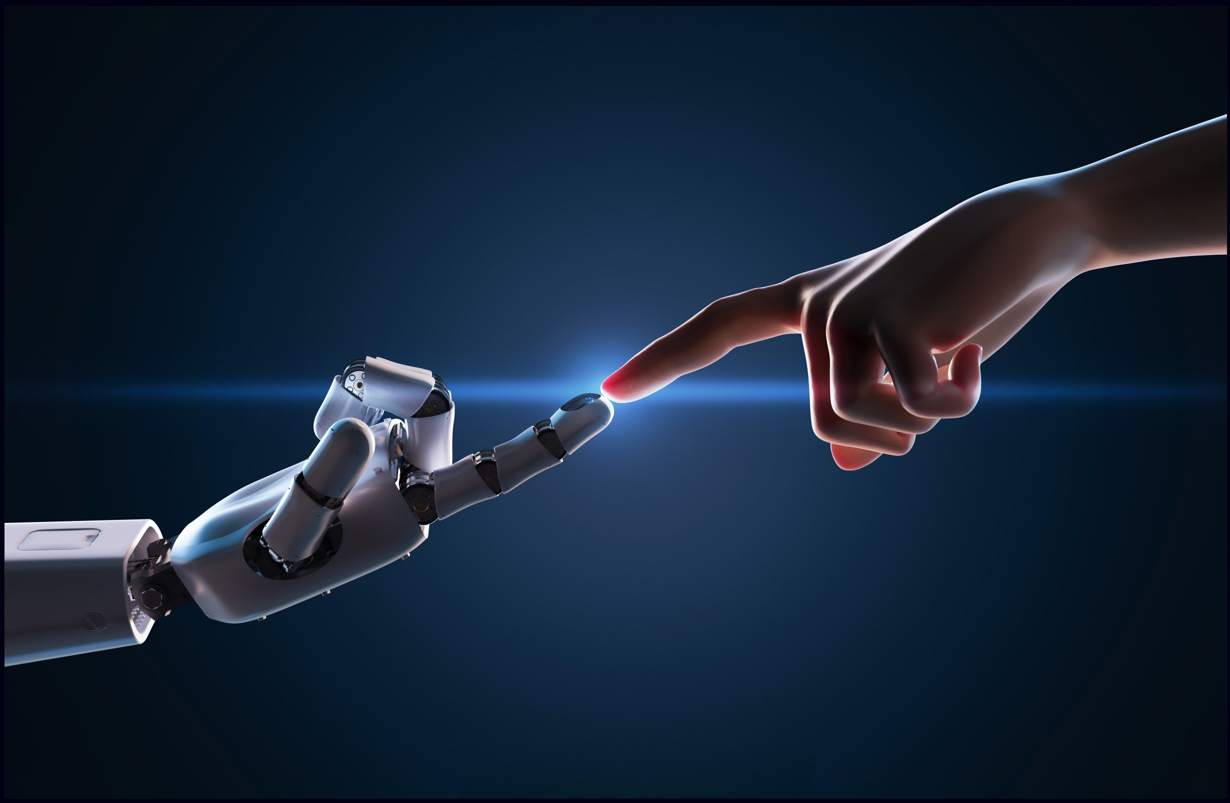
Towards Personalization of Robot-Assisted Motor Learning Based on User Characteristics

Haptic Guidance seems better suited for individuals with a more Internal rather than External Locus of Control

Caspar Hylke Willem Boersma



Towards Personalization of Robot-Assisted Motor Learning Based on User Characteristics

Haptic Guidance seems better suited for individuals with a more Internal rather than External Locus of Control

Thesis

by

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***Abstract*—Robots can aid in post-stroke motor function recovery and motor learning through the use of haptic feedback during collaborative training. A clear objective in robotic-assisted motor learning is to adapt the haptic feedback to individual users, but personal characteristics are not yet considered in this adaptation.**

We investigated the suitability of a haptic guidance feedback strategy, based on participants' locus of control character trait, compared to training without haptic guidance. For this purpose, a motor learning experiment was conducted on 42 healthy participants, where the internal dynamics of a pendulum had to be learned in order to hit upcoming targets. For two groups, training either with or without haptic guidance, we assessed motor learning and its generalization to similar tasks through target hitting performance, as well as behavior during training and perceived user experience.

Evidence was found of a relatively better performance improvement in both training and long-term (generalization of) motor learning for participants with a more internal compared to external locus of control. Lower observed interaction force during training and increasingly better performance throughout training in these participants may have caused these motor learning differences. More positive user experience in these individuals through a higher perceived control over the pendulum and lower perceived frustration with haptic guidance may have also contributed.

Combined, this suggests an intrinsically better compatibility with haptic guidance for people with a more internal rather than external locus of control, for motor learning, during training and in user experience.

***Index Terms*—motor learning, neurorehabilitation, robotic assistance, haptic guidance, locus of control, personalization, training strategy.**

I. INTRODUCTION

A. General Introduction

Individuals may have their own preferred way of learning a task [1] [2]. Take for example students that prefer learning a motor task, such as writing, together with a teacher; the teacher can grab the student's hand to collaboratively perform the movement. However, other students can prefer trying the task on their own, in which case the teacher does not have any physical interaction with the student at all.

Robotic devices can provide feedback forces in interactions with humans (Human Robot Interaction) through so-called Haptic Feedback [3]. The type of interaction the teacher has with the student in our example resembles Haptic Guidance, a robotic-assistance method where the robot guides the human along a pre-determined trajectory through correction forces, when deviating from this trajectory [4], similar to how a teacher would correct a student [5].

In this study, we investigated whether a personal suitability for learning a dynamic target hitting task, with or without this Haptic Guidance, is captured in the Locus of Control character trait. With these results, we intend to move towards personalization of robot-assisted motor learning, by selection of the best suited training method for an individual based on their characteristics. For this study, this selection can be seen as analogous to the decision of a teacher to allow a student either to learn the task independently, to engage in collaborative movement.

B. Background

A plethora of Haptic Feedback strategies exist in Human Robot Interaction for rehabilitation of motor functions after neurological trauma [4] [6] [7], or improvement of motor functions (i.e. Motor Learning) in tasks such as rowing or surgery [8] [9] [10].

The use of Haptic Feedback strategies is most effective in early treatment of stroke patients [11] [12], where the robotic strategies can provide repetitive, intensive and task specific training deemed necessary for optimal functional outcomes of recovery [13]. The efficacy of Haptic Feedback in Motor Learning for healthy or less-impaired subjects, shows conflicting results [14], and depends on the type of the strategy applied [3], which ranges from different sorts and degrees of assistance, to the intentional resisting of users, or amplification of their errors [7].

To improve overall efficacy of Haptic Feedback methods, calls have been made to adapt the strategy to the user [3] [4], and to investigate and model the underlying factors that drive Motor Learning [4].

C. State-Of-The-Art

Current strategies adapt parameters *within* a robotic strategy to suit a user during training, when the Haptic Feedback occurs, based on, for example, their psychophysiological state [15], or their performance during training [16] [8].

Little research has been performed to make a selection *between* strategies. One approach has been to adapt the modality of the feedback, switching between, or combining, haptic, visual and auditory feedback types, based on performance during training [17] [18].

Another approach, in neurorehabilitation of motor functions after stroke, is the use of interactive games in Virtual Reality [19], not necessarily in combination with Haptic Feedback. Recently, advances have been made to adapt game properties, such as objectives or rewards, to suit individual characteristics as captured in one's preferred game style [20], in order to increase engagement and intrinsic motivation, two of the main driving factors in Motor Learning according to Wulf and Lewthwaite's OPTIMAL theory [21][22].

D. Problem Statement

Adaptation to individual characteristics, as is already done within Virtual Reality tasks, is currently not performed when deciding an optimal *Haptic Feedback* method for users during training. Furthermore, a large variability is present between the degree to which users are affected by Haptic Feedback methods, relating to aspects such as the perceived agency, helpfulness, predictability and resistance [23].

We believe that underlying characteristics and preferences are the source of these differences, contributing to the wide range of Motor Learning outcomes observed among individuals [18]. Moreover, we think that applying a Haptic Feedback method that is incompatible with an individual's characteristics, or intrinsic preferences, will inherently hamper them in fulfilling their full Motor Learning potential, regardless of any further optimization of underlying parameters within that method.

E. Research Objective

Previous research has shown that the recovery Locus of Control character trait affects recovery in stroke patients', depending on whether they received conventional walking therapy or robot-assisted walking therapy, which includes Haptic Guidance for feet trajectories [24]. Our objective is to investigate whether the Locus of Control (see Section I-G for a definition) describes an intrinsic suitability for robot-assisted Haptic Guidance for motor learning, by comparing motor learning results to training without Haptic Guidance. Additionally, we aim to investigate whether any potential differences in Motor Learning depending on the Locus of Control, can be attributed to participants' perceived User Experience, or their Performance and Robot Interaction during Training. Positive results could potentially be used to aid in selecting the best suited training strategy for new users, depending on their Locus of Control charecter trait.

We summarized our objective in the following Research Question:

Research Question. *"Is Haptic Guidance better suited for individuals with a more Internal than External Locus of Control in Motor Learning, during Training and with respect to their User Experience, compared to training without Haptic Guidance?"*

F. Approach

We use the same Pendulum Task, and a similar implementation of the Haptic Guidance strategy developed by Özen et al. [25] to perform a motor learning experiment on 42 healthy participants. The participants were divided into two groups: the Experimental Group (E), who received Haptic Guidance during training for the task, and the Control Group (C), who did not receive Haptic Guidance. Participants had to move the pivot point of a pendulum to hit incoming targets with the mass on the other end of the pendulum [25]. We analyzed whether differences are present between users based on their Locus of Control in the following three topics.

1) Motor Learning:

The impact of the Locus of Control on Motor Learning was investigated, by comparing performance in assessment tests before Training (Baseline) to after Training (Short- and Long-Term Retention). Evaluation was done through a **performance outcome metric** that reflects task achievement.

In the previously mentioned gait rehabilitation study, Bragoni et al. found no differences in motor rehabilitation outcomes in their control group, using conventional rehabilitation, depending on the recovery Locus of Control (RLOC) [24] [26]. Although on group level no significant differences were found between effectiveness of both rehabilitation methods, in the group who finished robotic treatment, they found that people with an Internal Locus of Control had relatively better motor rehabilitation outcomes compared to people with External Locus of Control. The RLOC variable explained almost 80% of the variance in the gait recovery for this group. We expect that these results generalize to our experiment according to the following hypothesis:

Hypothesis 1. *Training with Haptic Guidance will lead to relatively better Motor Learning for people with a more Internal than External Locus of Control, whereas no effect of the Locus of Control is present on Motor Learning after training without Haptic Guidance.*

2) Training:

Relative differences in motor learning with Haptic Guidance can originate from the way people perform during or interact with robot-assistance during training [3], where 'slacking', decreased effort and engagement due to excessive reliance on robotic support, can hamper motor learning [4]. Therefore, we will assess the performance metric, but also **interaction outcome metrics**, relating to the interaction between robot and human, in participants who train with the Haptic Guidance strategy, to investigate whether the interaction with the Haptic Guidance strategy depends on one's Locus of Control.

Takayama et al. [27] found that individuals with an Internal Locus of Control had relatively longer completion times in an obstacle course, especially when receiving robot assistance. Acharya et al. [28] observed that individuals with an Internal Locus of Control provided more commands and relatively more opposing commands with respect to the robot assistance during an obstacle avoidance task, supported by the results of a follow-up study [29]. These studies indicate that individuals with an Internal Locus of Control tend to deviate from robot-assisted trajectories, and interact much with robotic assistance. This could indicate higher engagement and/or effort during training, compared to individuals with a more External Locus of Control, and leads to the following hypothesis:

Hypothesis 2. *There is more interaction with and deviation from the Haptic Guidance reference trajectory for people with a more Internal than External Locus of Control.*

3) User Experience:
People's perceptions and subjective experiences during training can be another source of relative motor learning differences. For example, allowing individuals to autonomously exercise control over training strategies has been shown to positively impact both motor learning and intrinsic motivation [21] [22].

Sense of Agency (see Section I-G for a definition) was lower after real world hand movements of subjects were manipulated in the way they were rendered in a Virtual Reality environment [30]. Both Dewez et al. and Jeunet et al. [31] [30], found that Internal Locus of Control correlated with Sense of Agency. The latter hypothesized that participants with an Internal Locus of Control tend to feel in control, despite disturbing effects of external factors.

Training with Haptic Guidance has a similar negative effect on people's Sense of Agency, by decreasing the perception of being in control over, or the cause of, pendulum movements [25], and leads to a significantly lower perceived control over the collaborative interaction during a tracking task [23] compared to other assistance methods. We expect that this negative effect is relatively lower in people with an Internal Locus of Control, and therefore obtain the following hypothesis:

Hypothesis 3. *There is a smaller decrease in Sense of Agency after collaborating with Haptic Guidance for people with a more Internal Locus of Control than External Locus of Control.*

We are also interested to find out whether this hypothesized more positive user experience in people with a more Internal Locus of Control extends to perceived Intrinsic Motivation with respect to the pendulum task, but also Frustration revolving around collaboration with Haptic Guidance.

G. Definitions

The personality trait **Locus of Control (LOC)**, which stays relatively stable throughout time [32], refers to *the belief of an individual about the degree to which they, as opposed to other factors, have control over events or outcomes that follow a behavior, or action, from this individual* [33] [34]. A tendency to attribute control to oneself is denoted as an "Internal" Locus, whereas a tendency to attribute control to other factors, such as luck, chance, faith or powerful people, is denoted as a more "External" Locus [35].

The **Sense of Agency (SoA)** is defined as "*the feeling of controlling an external event through one's own action*" [36]. It is related to specific events and the way a person perceives their own agency in that particular situation.

In other words, while Sense of Agency is context-specific and relates to a person's feeling of being in control in a particular moment, Locus of Control concerns a more overarching worldview about who, or what, controls a person's life through the results or consequences of their actions.

II. Methods

A. Experimental setup

The experiment was performed with the Delta.3 robot (Force Dimension, Switzerland). The pendulum Game, implemented in Unity (Unity Technologies, US) with C#, and the motion control of the robot, implemented in C++, were obtained from Özen et al. [25]. The combined system records user data at a frequency of 1.67 kHz.

In Figure 1 a participant can be seen while playing the pendulum Game. The end-effector of the robot in this figure corresponds to the end-effector of the pendulum, as shown in Figure 2-A.

B. The pendulum Dynamics

The robot serves as a haptic interface, where a participant applies forces to the robot end-effector. Through these forces, the robot end-effector accelerates, which results in an equal in-game acceleration of the pendulum end-effector (1-to-1 mapping). The acceleration of the end-effector causes a change in the internal state of the pendulum, namely the pendulum angle θ, visible in Figure 2-A.

The relationship between the swinging motion of the pendulum (θ) and the end-effector movements (z, y) is described by the following equation:

$$\ddot{\theta} = -\frac{1}{l}\Bigg(\big(\ddot{z} + g\big)\sin(\theta) + \ddot{y}\cos(\theta)\Bigg) - \frac{c}{ml^2}\dot{\theta}. \quad (1)$$

The constants in this equation were set to the same values as prior research [25] as follows. The pendulum coefficients: the ball mass m, the rod length l and the damping coefficient c, are 0.600 kg, 0.250 m and 3.00e^{-6} N·s/rad respectively. The gravity coefficient, g, equals 1/3 of the world's gravity, resulting in a value of 3.24 m/s^2. With these constants, a pendulum natural frequency (ω_N) of 0.573 Hz is obtained through the following equation:

$$\omega_N = \frac{1}{2\pi}\sqrt{\frac{g}{L}}. \quad (2)$$

Forces from the pendulum dynamics, originating from inertia of the pendulum mass (m), are rendered to the user (haptic rendering). These forces can be perceived by the user through the end-effector, to accommodate realism in controlling the pendulum [37]. The haptic rendering forces are calculated through the following equation:

$$F_{\text{rod}} = m\Bigg(\big(\ddot{z} + g\big)\cos(\theta) - \ddot{y}\sin(\theta) + \dot{\theta}^2 l\Bigg). \quad (3)$$

The equations of motion of the pendulum (Equations 1 and 3) were derived in [38], and a further overview of the implementation is given there as well.

C. The pendulum Game

1) General Description:
The pendulum Game revolves around hitting vertical orange targets with the red pendulum ball (Figures 1 and 2). These targets are located in yellow/black blocked walls that approach the participant with one second intervals, in sets of 20 walls [25]. Between sets, there is an interval, without targets, of three seconds. Walls are located at three possible positions in a wall: either at the center ($y_{\text{target}} = 0$ m) or a distance of b

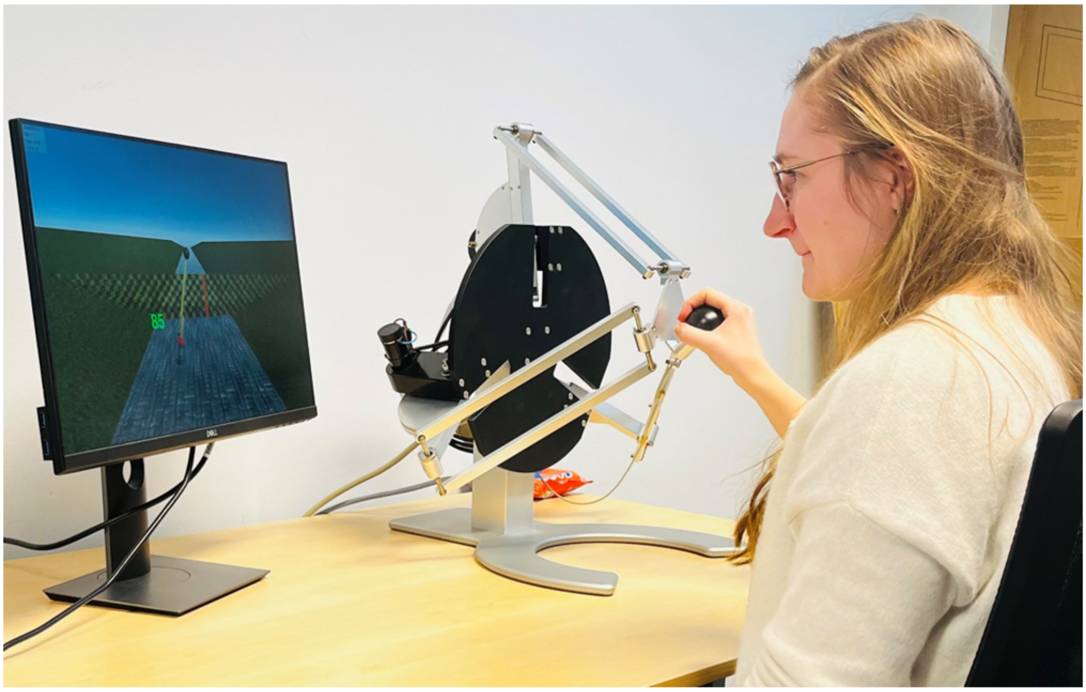

Fig. 1: Experimental Setup with a participant interacting with the Force Dimension Delta.3 robot when playing the pendulum Game.

= 0.12 m from the center ($y_{\text{target}} = \pm 0.12$ m), as visible in Figure 2-B.

Three different tasks are implemented, that differ in either target locations or implemented pendulum dynamics (see Sections II-C3 and II-C4). Figure 1 shows an example of the pendulum Game in practice can be seen in, where the participant moves the black robot end-effector with her hand, which is rendered in-game by the same movement of the black pendulum end-effector, thereby indirectly controlling the red pendulum ball to hit an upcoming target.

2) Objective of the Game:
Effectively, the objective in the pendulum Game consists of minimizing the Absolute Error ($ErrorAbs$ (m)) to obtain high accuracy in hitting the upcoming targets. The Absolute Error is calculated by taking the absolute y-distance between the red pendulum ball and the vertical target at the moment of passing an upcoming wall, according to Equation 4. An example can be seen in Figure 2-B. In this case, a target is located at y-position 0 (y_{target}), with the Ball at a negative y-position of -a (y_{ball}).

$$ErrorAbs = |y_{\text{ball}} - y_{\text{target}}| \quad (4)$$

The $Score$ for a target is shown in green to participants for 0.5 seconds after passing the respective target (Figure 1), to provide quantitative performance feedback, which can aid in increasing motivation [25]. This variable is based on the Absolute Error, according to Equation 5 [25] [39].

$$Score = \begin{cases} 0 & \text{if } ErrorAbs \geq 0.2 \\ 100 - 500 \cdot ErrorAbs & \text{else} \end{cases} \quad (5)$$

If a $Score$ of 0 is obtained, it is shown in red instead of green. After each set of 20 targets, the mean $Score$ for the set is shown to the participant.

3) Main Task:
Participants are assessed in the Main Task, the same task as used during training (see Figure 3). The 20 targets of the Main Task are positioned at fixed locations within each set, to maintain a constant nominal (i.e. inherent) difficulty level, and to facilitate data analysis. The exact placements of the targets can be found in Appendix D, Table VI.

The Main Task target locations are selected to present users with a moderate to high level of nominal task difficulty. A lower nominal difficulty was avoided, as it could leave too little room for improvement throughout training. In such a scenario, we risk that most participants achieve near-perfect $Score$ after training, and any improvement would primarily depend on their initial skill level.

4) Transfer Tasks:
The pendulum Game contains two Transfer Tasks, to determine whether any motor learning during training in the Main Task generalizes to similar other tasks [3]. We used a Target Transfer Task, and a Dynamics Transfer Task [39].

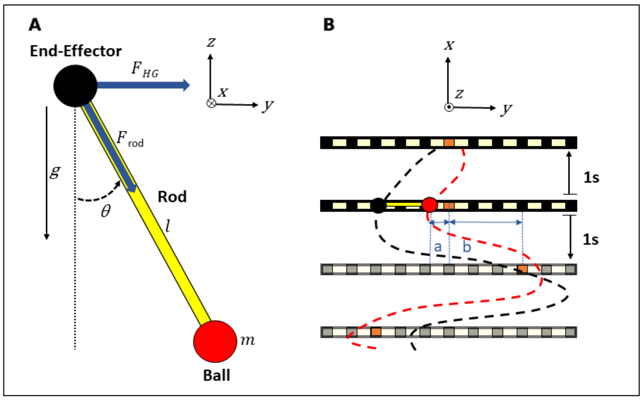

Fig. 2: **(A)** The pendulum free body diagram, with a front view of the pendulum. **(B)** Example of a top view of the game. The red dashed line represents the ball trajectory and the black dashed line the end-effector trajectory through time, where the lighter colored walls have been passed earlier in time. Darker colored walls approach the pendulum and reach it with a one-second interval. The x-axis is redundant, because the end-effector is kept at a constant x-value of zero by a stiff PD-controller. The $ErrorAbs$ metric is calculated by taking the absolute distance between the target and the ball at the instance a wall is passed (a). Targets are either placed in the center of the game (y-value of zero) or at a distance of 0.12 m left or right (b) from this center.

The Target Transfer differs from the Main Task in the target locations, which can be seen as analogous to driving the same car on a different racetrack [39]. We aimed for a higher nominal task difficulty compared to the Main Task, see Appendix D, to assess the adaptability and versatility of learned skills to situations that are closer to real-life, where tasks can be more complex.

In the Dynamics Transfer, the pendulum dynamics are altered, analogous to driving a different car on the same racetrack [39]. The pendulum length l is scaled with 0.7, while visually rendering the original length in-game [39]. This affects the pendulum dynamics by changing the natural frequency from 0.573 Hz to 0.685 Hz through Equation 2. Equation 1 dictates that a decrease in pendulum length results in an increased pendulum angular acceleration in response to the same end-effector acceleration, making the pendulum more responsive to human movements. Simultaneously, the equation shows that a decrease in length results in a higher damping effect, leading to faster stabilization after human movements.

D. Haptic Guidance

The Experimental Group received robotic assistance during training, whereas participants from the Control Group performed the task by themselves. The implementation of the Haptic Guidance (HG) robot strategy consists of two parts, calculation of a reference trajectory for the pendulum end-effector, and enforcing this reference trajectory through a Proportional Derivative (PD) controller. The Haptic Guidance strategy used [25], was altered to fit the current experimental purpose. See Appendix A for a detailed description of the implementation.

1) Reference Trajectory:
The reference trajectory is determined on a target level: when the pendulum is in the range of a wall, i.e. one second before this next wall will be hit, an optimization is performed. The optimization is implemented using the ACADO toolkit [40], a C++ implementation for solving non-linear, optimal control problems, and it uses the dynamic system of the pendulum to calculate y-positions of the pendulum end-effector. This method primarily optimizes for assistance in target hitting, and stabilization of the pendulum swing, while simultaneously avoiding uncomfortably high end-effector amplitudes, see Part B of Appendix A.

2) Enforcing the Trajectory:
The pendulum y-positions of the end-effector, are employed as a reference for the PD-controller after a cubic spline fit transforms the y-positions to the system frequency of 1.67 kHz. The error ($e(t)$) between the actual end-effector position and the reference at the same time step, together with its derivative ($\frac{d}{dt}e(t)$), are used in Equation 6 to obtain the Haptic Guidance force in y-direction (F_{HG}), with proportional gain K_p of 75.0 N/m and derivative gain K_d of 15.0 N·s/m.

$$F_{HG} = K_p e(t) + K_d \frac{d}{dt} e(t). \tag{6}$$

E. Participants

The experiment was performed on 42 participants, similar to [24], who were inexperienced with the pendulum Task. All the participants provided written consent to participate in the study, which was approved by the TU Delft Human Research Ethics Committee (HREC). Of the 42 participants, two were excluded from analysis; one due to highly deviating initial skill level, as their performance at baseline was more than three standard deviations lower than the average of all participants, and one due to missing data because of a corrupted output file of the Delta.3 robot.

Of the remaining participants (19 female/21 male, mean age: 27 years, std. deviation: 6 years), four are left-handed and one ambidextrous, according to the Short-Form Edinburgh Handedness Inventory [41]. Participants interacted with the robot with their preferred hand, which was in line with their Edinburgh Handedness results for all participants, including the ambidextrous person (slight right-hand preference). The experiment was performed at two locations, TU Delft and Alten Netherlands, and the participants received a gift voucher of €15 for their participation.

The first half of the participants was randomly allocated to either the Control Group or the Experimental Group. The second half of the participants was allocated pseudo-randomly, to obtain balanced groups based on number of participants, sex distribution, and Locus of Control distribution, similar to the method used in [42].

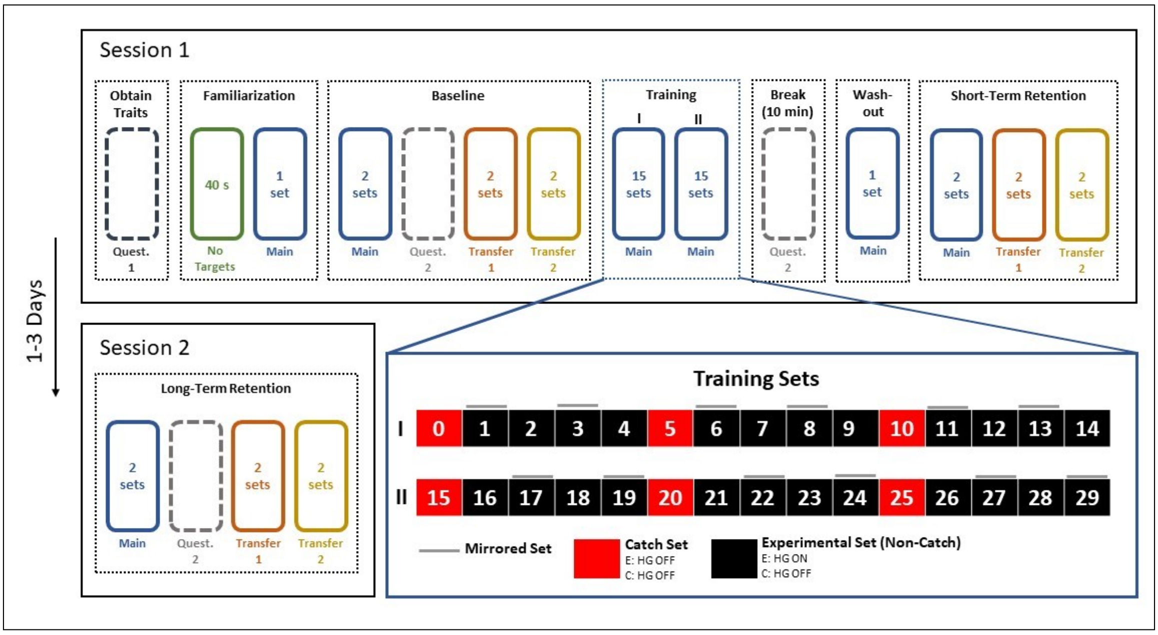

Fig. 3: The Experimental Protocol. Participants were distributed pseudo-randomly over the Control Group (C) and Experimental Group (E), for whom the experiment differed in the Training phase, where the Experimental Group received Haptic Guidance (HG) during the black Experimental sets.

F. Study Protocol

The experiment consisted of two sessions, separated by 1-3 days, for a total duration of approximately 1 hour and 15 minutes. The Experimental Protocol can be seen in Figure 3. Haptic Guidance is only present during training, exclusively for the Experimental Group. In the assessment tests, the assistance was disabled to be able to accurately evaluate the participants' skill level, without any interference with performance resulting from Haptic Guidance [3]. The haptic rendering of the pendulum forces is present throughout the entire experiment for all participants.

Session 1 started with signing the informed consent form, followed by filling in the Trait Questionnaire including the Locus of Control scale (see Appendix B), and demographics, as well as other traits to be used in future research, including the Hexad Gaming Style [43] and Autotelic Personality [44].

1) Familiarization:

After visual and verbal instruction to explore the limits of the robot workspace, participants familiarized with the set-up during 40 seconds in the game environment without rendered targets. Afterward, chair height could be adjusted to personal preference, ensuring comfortable arm movements for the whole workspace. Participants were visually and, if necessary, verbally instructed of the pendulum task objective. To take initial performance variability and inconsistent movement observed among participants into account, which may stem from different initial task strategies [39], a trial set of the Main Task was subsequently incorporated. Additionally, we intended to decrease performance anxiety with this, as participants can briefly familiarize with the task, without the added pressure of immediate experimental performance.

2) Baseline Assessment:

The Baseline assessment was performed to obtain an estimate of the initial skill level of all three tasks [39], with a set length of 20 targets, which is repeated for each task [25]. During this Baseline Stage, the baseline User Experience (Sense of Agency and Intrinsic Motivation) was obtained for each participant through Questionnaire 2 (see Appendix C), directly after performing the Main Task.

3) Training:

The experiment differed in the Training phase, where the Experimental Group received Haptic Guidance during the sets showed in black (Experimental sets) in Figure 3. Six Catch-sets were added to be able to compare performance during Training with- and without HG within participants from the Experimental Group. There was an opportunity to take a short break after the first 15 sets of the Training phase (Training part I) before starting the 15 sets of Training part II.

The target positions were mirrored around the y-axis in half of the Training sets, to keep this relatively long Training phase, of 30 sets in total, engaging [39] [25]. Additionally, this type of modification does not seem to affect task performance [39]. The mirrored sets were non-randomly allocated, and shifted in Training part II relative to Training part I, resulting in a mirrored set order that is reflected around set 15.

4) Break & Washout:

After Training, participants were presented Questionnaire 2 again, to see whether differences in subjective sense of Agency and Motivation with respect to Baseline occur. Here, participants in the Experimental Group are presented three extra questions, as shown in Section II-G4, to rate their subjective experience with respect to the HG strategy.

Participants started the Wash-Out 10 minutes after ending Training to provide time for recovery from possible muscle fatigue. The Wash-Out consisted of one set of the Main Task, to allow participants from the Experimental Group to lose potential after-effects of the Human Robot Interaction with the HG strategy [25].

5) Retention Assessment:
The tasks and lengths of the sets used in Short-Term and Long-Term Retention Stage repeat those of the Baseline Stage, to allow fair comparison. The Long Term-Retention takes place 1-3 days after the initial session [25] [39].

G. Outcome Metrics

1) User Characteristic Outcome Metric:
This research revolves around the **Locus of Control** (LOC), which we determine through Rotter's Locus of Control Scale [33] (Appendix B). This scale is widely used in literature [28] [27] [45] [46], and outcomes are found to be stable throughout time [47] [48], substantiating its use as an intrinsic user characteristic in our research.

Rotter ranks a person on an integer scale in the range [0, 23] through self-evaluation, with 0 denoting an entirely Internal Locus of Control and 23 a fully external Locus of Control. We transformed the 24 possible values for the variable to floats in the range [-1, 1], to enable more intuitive interpretation: more negative values describe an increasingly Internal LOC, whereas more positive values an increasingly External LOC.

2) Motor Learning Outcome Metrics:
The objective of the Pendulum Game is to minimize the Absolute Error obtained at the moment a target is hit, as described in Section II-C2. We evaluate the effect of the Locus of Control on Motor Learning, by investigating changes in the *Absolute Error* ($ErrorAbs$) **performance metric** between Baseline and Retention targets. A decrease in this metric denotes an increase in performance, as the underlying target is hit more accurately with a lower error.

3) Training Outcome Metrics:
In addition to the performance metric, we evaluate the **interaction metrics** during training. We take the *Estimated Absolute Interaction Force* ($IntForceAbs$ (N)) [25] and take the mean to obtain a data point per target of the Interaction Force between robot and participant. The estimation is performed by Reaction Torque Observers [49] as implemented by Özen et al. [25]. The magnitude of the Interaction Force can increase when Haptic Guidance and participant oppose each other, thereby showing to what extent participants interact with the Haptic Guidance strategy. For the Group training with Haptic Guidance, this interaction force may lead to deviation from the reference trajectory, which we measure with the mean *Absolute Deviation From the Reference* ($DevRefAbs$ (m)) per target.

4) User Experience Outcome Metrics:
User Experience was investigated with self-reported aspects regarding participants' Task Experience and Robot Interaction Experience. **Task experience** was separated into Sense of Agency and Intrinsic Motivation.

Sense of Agency was administered through an adapted version of the Sense of Agency Questionnaire by [50], as used in [25] and [39]. Due to low internal consistency and reported difficulty in interpretation by participants of one of the questions in this Questionnaire ("It seemed as if the pendulum was controlling me") [39] and recommendation by the main author from [25], we removed that specific question. The remaining two questions revolve around perceived *Control of the pendulum* ($pendulumControl$ (-)) and perceived *Cause of the pendulum Movements* ($pendulumCauseMovements$ (-)), where we take the mean per participant per Questionnaire moment to obtain $AgencyMean$ (-).

Intrinsic Motivation was obtained using the Intrinsic Motivation Inventory (IMI) [51] subscales *Interest/Enjoyment* (-), *Perceived Competence* (-), *Effort/Importance* (-) and *Pressure/Tension* (-) [52]. From these subscales, the same subset of three questions was used as in [25] and [39], including the same randomized order for each participant. Additionally, one question from the Interest/Enjoyment subscale was added to the end of the IMI questions, about perceived boredom of the task, which was not used in analysis within the current research.

Robot interaction experience with respect to Haptic Guidance, consisted of three questions, added to Questionnaire 2 after Training for the Experimental Group. Perceived $Frustration$ (-), was measured to verify whether differences in perceived Frustration are present based on the Locus of Control trait. We developed the following question for this purpose: "*The robot interaction frustrated me*". This question was answered through a 7 point Likert-scale, in line with the IMI [51] (1–not at all true, 7–very true).

Additionally, the question "*Was the interaction disturbing or helpful?*" from [23], was modified by changing "interaction" to "robot interaction", to verify whether our Haptic Guidance aids participants in the task. For this $Disturbing\ vs.\ Helpful$ (-) variable, we used the same scale range as the Sense of Agency Questionnaire, i.e. to "-3/+3: very disturbing/helpful". $Restricting\ vs.\ Permitting$ (-), was measured to verify if participants indeed perceived the Haptic Guidance to a reference trajectory as restrictive. Along the same lines as the previous question, we developed the following question ourselves: "*Was the robot interaction restricting or permitting your own movements?*" with the scale "-3/+3: very restricting/permitting".

H. Statistical Analysis

In our analysis, the level of significance was set at $\alpha = 0.05$. The *lmer* model type from the *lme4* package [53] in R was used to implement Linear Mixed Effect Models, as it allows white-box modeling in combination with extensive statistical analyses. Regression lines of these models and their associated statistical results were visualized with the *sjPlot* package, using the *plot_model* and *tab_model* functions, respectively. Residuals of the fitted models are inspected visually through QQ-plots.

Models were generally fitted twice for each metric: once with the Control Group as the reference and once with the Experimental Group as the reference. The two fits result in identical regression lines, as data and underlying regression formula remain the same. However, using one Group as the reference in the *lmer* model enables interpretation of effects within that specific Group. For some outcome metrics, only Experimental Group data is available, so no additional fit for the Control Group is possible.

Contrary to prior research [25] [39] that relied on the mean of outcome metrics per set for statistical analysis, our approach involved calculating either the mean per target for interaction outcome metrics, or the unaltered Absolute Error per target for the performance outcome metric. This approach resulted in a larger sample size with more detailed data, and enabled us to evaluate the effect of outcome metrics within sets.

The following variables were used in analyses in Motor Learning, Training and User Experience, and are therefore introduced here.

- $Group$: the Group of a participant indicates whether they were assigned to the No Haptic Guidance (C) or Haptic Guidance (E) condition during training. Models for which only Haptic Guidance data is available do not include this variable.
- ID: the participant ID, represented by a string, serves as a unique identifier for associating a data point with a specific participant. In our models, we incorporate it as '$(1|ID)$', a random regression intercept per participant. This allows us to capture similarities among outcome metrics of the same participant, as well as differences between data points from different participants that are not accounted for by our independent variables [54].

1) Motor Learning Statistical Analysis:
The Motor Learning Analysis consists of a comparison of assessment test performance from before and after Training. For the Transfer Tasks, the outcomes represent the Generalization of Motor Learning. The variables used in the analysis include:

- $Stage$: this variable represents the assessment test Stage where a data point was obtained, starting with Baseline (BL), followed by Short-Term Retention (STR) and Long-Term Retention (LTR), which both occur after training. This variable is modeled as a factor in R.
- $sIndex$: each assessment test consists of two sets per Task. The $sIndex$ variable denotes the index of the set for a specific Task by either 0 or 1, where set 0 is performed first.
- $wIndex$: the index of a wall (containing a target) in a set, ranging from 0 to 19 as there are 20 targets per set.

The formula used for the *lmer* model type in the Motor Learning analysis, is shown in Equation 7, with the Absolute Error as dependent variable.

$$ErrorAbs \sim LOC * Stage * Group + wIndex + sIndex + (1|ID) \quad (7)$$

General Motor Learning: we used Equation 7 for multiple comparisons with Tukey's Honest Significant Difference (HSD) test [55], using the *emmeans* package in R, to evaluate Motor Performance both within Groups between Stages and between Groups within Stages. The former was done to determine whether Motor Learning occurs after Training, and the latter to determine whether initial performance differences are present between our two Groups, which could bias motor learning results [3]. Similarly, Motor Learning between Stages was compared among Groups, to validate whether a Training method was showing overall better Motor Learning, without taking the Locus of Control into account. P-values are adjusted with False Discovery Rate [56], as Tukey's HSD is not appropriate for two sets of pairwise comparisons.

Locus of Control & Motor Learning: we compared the regression line of the Locus of Control of the Experimental Group at Baseline, to the regression line of the Locus of Control of the same Group at either Retention stage, to evaluate whether the Locus of Control affects Motor Learning when training with or without Haptic Guidance.

The term $LOC{*}Stage{*}Group$ denotes that the fixed effects of the three variables, as well as all their possible interaction effects, are included in the underlying regression. This enables the following evaluation:

- Hypothesis 1 relates to the interaction effects between LOC at Baseline and either Short-Term or Long-Term Retention $Stage$. These effects describe whether Locus of Control influences the change in Task performance for the reference Group. Thus, a significant result indicates that individuals in the reference Group show varying performance changes throughout assessment Stages based on their Locus of Control trait.
- We also investigate whether the aforementioned relative performance changes, influenced by Locus of Control, differ between those training with Haptic Guidance and those training without it. To assess this, we examine the interaction with the $Group$ variable through the $LOC \times Stage \times Group$ double interaction effect.

2) Training Statistical Analysis:
The Training analysis models effects of the Locus of Control of both Performance and Robot Interaction during Training. The variables used in the resulting models are:

- $trIndex$: the Set Index during Training, which ranges from 0 for the first set of Training part I, to 29 for the last set of training part II (see Figure 3).
- $wIndex$: the index of a wall containing a target within a set, ranging from 0 to 19.

The $Metric$ in Equation 8 can be either Absolute Error or Absolute Interaction Force. The formula contains the term $LOC * trIndex * Group$, denoting the inclusion of the fixed effects of the three variables and all possible interaction effects between them in the underlying $lmer$ regression.

$$Metric \sim LOC * trIndex * Group + wIndex + (1|ID) \quad (8)$$

The data used in this analysis only consists of the Experimental, i.e. Non-Catch sets, for both Groups, to be able to compare the effect of Locus of Control on Training with and without Haptic Guidance between Groups. The Control Group did not receive Haptic Guidance forces during the analyzed Experimental Sets, but only experienced forces from Haptic Rendering or non-transparent behavior of the ForceDimension Delta.3 robot. For the Absolute Deviation from the Reference outcome metric, Equation 8 was used without inclusion of the $Group$ variable. This was due to the absence of a reference trajectory during training without Haptic Guidance, thus no data for this particular type of robot interaction is available for that Group.

Our analysis focused on the following aspects:

- Fixed effects of the Locus of Control variable on the outcome metrics, representing a consistent effect on the outcome metric by the Locus of Control.
- The interaction effect between Locus of Control and $trIndex$, which represent that for the reference Group, the effect of the Locus of Control on the outcome metric changes throughout Training.
- Whether any of the previous two types of effects are different between Groups, denoted by their interaction with the $Group$ variable.

3) User Experience Statistical Analysis:

Task Experience: the Task Experience analysis revolves around data from Questionnaire responses about User Experience specifically aimed at contents of the task performed directly prior to the Questionnaire. The variable specific to this analysis is:

- $Quest$: denoting the moment at which data was obtained through Questionnaire 2, either at Baseline (BL), after Training (TRN) or during Long-Term Retention (LTR). This variable is modeled as factor in R.

Formula 9 was used for each of the Sense of Agency questions ($AgencyControl$ and $AgencyCauseMovements$) and the mean of both questions. Additionally, the formula was used with the selected subscales of the Intrinsic Motivation Inventory as dependent variable. Since the same model was used for both Agency and Motivation, we describe them collectively by $Task\ Experience$.

$$Task\ Experience \sim LOC * Quest * Group + (1|ID) \quad (9)$$

The evaluation had the following focus:

- For Hypothesis 3, especially interaction effects between the Locus of Control and the TRN Questionnaire with Sense of Agency questions as dependent variables are of interest. These effects describe the relative change in Sense of Agency for the reference Group from Baseline to after Training, depending on the Locus of Control.
- For such significant interaction effects, the correlation (Pearson's R) of the Locus of Control with a participant's difference in Sense of Agency at Baseline and after Training is calculated.

Robot Interaction Experience: to determine whether Haptic Guidance was perceived as helpful and restricting, we take the mean and standard deviation of the responses from the Perceived Helpfulness and Perceived Restriction questions, similar to the method used in [57].

To determine whether perceptions of participants regarding the Haptic Guidance correlate with Locus of Control, we employ the formula from Equation 10 using the *lm* model from the *lme4* R package. $RobotInteractionExperience$ represents either $Frustration$, $Disturbing\ vs.\ Helpful$ or $Restricting\ vs.\ Permitting$ as dependent variable.

$$RobotInteractionExperience \sim LOC \quad (10)$$

III. Results

A. Motor Learning Results

	Comparison		ErrorAbs (m)		
Task	**Stage**	**Group**	**Estimate**	**Std. Error**	**p-Value**
Main Task	STR-BL	C	-0.025894	0.00221	**<.0001**
	LTR-BL		-0.025681	0.00221	**<.0001**
	LTR-STR		0.000213	0.096	1.0000
	STR- BL	E	-0.024885	0.00221	**<.0001**
	LTR-BL		-0.026328	0.00221	**<.0001**
	LTR-STR		-0.001444	0.00221	0.9867
	BL	E-C	-0.000335	0.00442	1.0000
	STR		0.000674	0.00442	1.0000
	LTR		-0.000983	0.00442	0.9999
Target Transfer	STR-BL	C	-0.029466	0.00206	**<.0001**
	LTR-BL		-0.024491	0.00206	**<.0001**
	LTR-STR		0.004976	0.00206	0.1511
	STR-BL	E	-0.023935	0.00206	**<.0001**
	LTR-BL		-0.023012	0.00206	**<.0001**
	LTR-STR		0.000923	0.00206	0.9977
	BL	E-C	0.000502	0.00428	1.0000
	STR		0.006034	0.00428	0.7208
	LTR		0.001981	0.00428	0.9973
Dynamics Transfer	STR-BL	C	-0.019215	0.00200	**<.0001**
	LTR-BL		-0.019865	0.00200	**<.0001**
	LTR-STR		-0.000650	0.00200	0.9995
	STR-BL	E	-0.009916	0.00200	**<.0001**
	LTR-BL		-0.013126	0.00200	**<.0001**
	LTR-STR		-0.003210	0.00200	0.5946
	BL	E-C	-0.005360	0.00461	0.8550
	STR		0.003939	0.00461	0.9572
	LTR		0.001380	0.00461	0.9997

TABLE I: Performance Comparisons: Comparisons of Absolute Error at a Stage between Groups and Comparisons of Absolute Error between Stages within a Group. P-values are determined through Tukey's Honest Significant Difference method. Significant p-Values are printed in bold.

1) General Motor Learning:

Table I shows that for each Task, Motor Learning occurs from Baseline to Retention (STR-BL and LTR-BL), both in the Group training with Haptic Guidance (E) and without Haptic Guidance (C); all of these comparisons have a p-value below 0.0001, combined with a negative estimate, denoting that the Absolute Error decreases significantly from Baseline to Retention (i.e. improvement in performance). Additionally, no significant difference in initial performance was found at Baseline between the Groups (E-C), or at either Retention Stage, for all Tasks.

	Comparison		ErrorAbs (m)		
Task	**Stage**	**Group**	**Estimate**	**Standard Error**	**p-Value**
Main Task	STR-BL	E-C	0.001009	0.00312	0.8357
	LTR-BL		-0.000648	0.00312	0.8357
	LTR-STR		-0.001657	0.00312	0.8357
Target Transfer	STR-BL	E-C	0.00553	0.00291	0.1721
	LTR-BL		0.00148	0.00291	0.6114
	LTR-STR		-0.00405	0.00291	0.2457
Dynamics Transfer	STR-BL	E-C	0.00930	0.00283	**0.0031**
	LTR-BL		0.00674	0.00283	**0.0259**
	LTR-STR		-0.00256	0.00283	0.3658

TABLE II: Performance differences compared between Groups: pairwise comparisons of Absolute Error during assessment test Stages within each Group, (Stage Comparison) for which the results are then compared between Groups (Group Comparison). P-values are adjusted with False Discovery Rate, and when significant, printed in bold.

Table II shows no significant difference in Motor Learning in both the Main and Target Transfer Task between Baseline and either Retention Stage (STR-BL or LTR-BL), when comparing the participants who received Haptic Guidance during training to the other Group. However, for the Dynamics Transfer there was a training method that led to better motor learning, namely in the Group without Haptic Guidance a larger performance increase was found from Baseline to either Retention Stage compared to the Group training with Haptic Guidance. This was represented by the positive estimates of the comparisons between Groups, with $p = 0.0031$ for STR-BL and $p = 0.0259$ for LTR-BL.

2) Locus of Control & Motor Learning:
Figure 4 visualizes the regression lines of the model based on Equation 7, for the term $LOC * Stage * Group$. The estimates of the effects related to a change in performance from Baseline to Long-Term Retention Stage are presented in Table III, with their respective significance level. A visualization of the underlying data used for each model can be found in Appendix H, in Figures 10-15. Table III does not show the Short-Term Retention Stage to facilitate interpretation, as this Stage does not show significant results with respect to Locus of Control. See Appendix H, Tables XI and XII for the complete regression results.

The right column of Figure 4 shows the Experimental Group performance for different Stages per Task. For this Group, from Baseline to Long-Term retention, a relatively higher decrease in Absolute Error is visible in all Tasks for a more Internal than External Locus of Control. For lower LOC values (more Internal Locus of Control), the Figure shows a greater difference between Baseline and Long-Term Retention Absolute Error, representing relatively higher performance improvement for Internal Locus of Control, which is in line with Hypothesis 1.

Positive estimates of $LOC \times Stage[LTR]$ indicate the previously described higher performance improvement for a more Internal Locus of Control, as they can be interpreted as the counter-clockwise rotations of the slope $ErrorAbs/LOC$ from Baseline to Long-Term Retention visible in Figure 4-

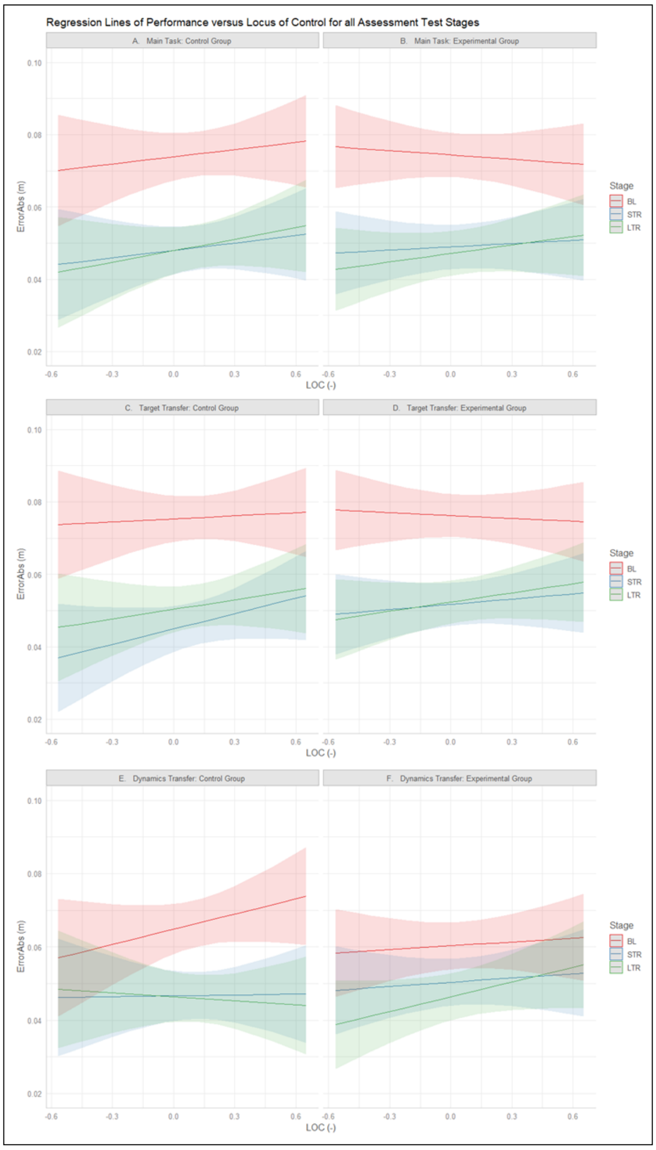

Fig. 4: Motor Learning regression lines of the $LOC * Stage * Group$ term (Equation 7), shaded with their 95% confidence interval. Each row shows a different Pendulum Task: **(A-B)** the Main Task, **(C-D)** the Target Transfer and **(E-F)** the Dynamics Transfer, with the first column the Control Group and the second column the Experimental Group.

A, B, C, D and F. In line with Hypothesis 1, these positive estimates are significantly present in the Experimental Group for the Main Task ($p = 0.041$) with significant Generalization to the Target Transfer ($p = 0.037$), and close to significant Generalization to the Dynamics Transfer ($p = 0.055$).

On the other hand, also in line with Hypothesis 1, this phenomenon is not present in the Control Group, where all estimates of $LOC \times Stage[LTR]$ are lower than in the Experimental Group, with non-significant p-values. Surprisingly, the estimate is so much lower in the Control Group during the Dynamics Transfer, that it is significantly below zero ($p = 0.010$) (Figure 4), suggesting a relatively higher

Outcome Metric ErrorAbs (m)		LOC			LOC x Stage[LTR]			LOC x Stage[LTR] x Group		
Task	**Group**	**Estimate**	**CI**	**p-Value**	**Estimate**	**CI**	**p-Value**	**Estimate**	**CI**	**p-Value**
Main Task	C	0.00664	-0.01416 – 0.02743	0.532	0.00393	-0.01078 – 0.01863	0.601	0.00779	-0.01070 – 0.02628	0.409
	E	-0.00392	-0.01977 – 0.01193	0.628	0.01172	0.00050 – 0.02293	**0.041**	-0.00779	-0.02628 – 0.01070	0.409
Target Transfer	C	0.00278	-0.01735 – 0.02292	0.786	0.00599	-0.00771 – 0.01969	0.392	0.00515	-0.01207 – 0.02238	0.558
	E	-0.00266	-0.01801 – 0.01269	0.734	0.01114	0.00070 – 0.02158	**0.037**	-0.00515	-0.02238 – 0.01207	0.558
Dynamics Transfer	C	0.01379	-0.00792 – 0.03551	0.213	-0.01747	-0.03079 – -0.00414	**0.010**	0.02741	0.01066 – 0.04416	**0.001**
	E	0.00348	-0.01307 – 0.02004	0.680	0.00994	-0.00021 – 0.02010	0.055	-0.02741	-0.04416 – -0.01066	**0.001**

TABLE III: Locus of Control regression results for Motor Learning. We present the effects on Absolute Error of: Locus of Control (LOC), the interaction between Locus of Control and the Long-Term Retention Stage ($LOC \times Stage[LTR]$). For the last effect, the interaction with $Group$ is shown as well ($LOC \times Stage[LTR] \times Group$). The Baseline Stage and the corresponding Group at each row are used as reference. The p-Values correspond to a two-sided t-Test and significant p-Values are denoted in bold ($p < 0.05$). Significant results related to the Locus of Control trait are highlighted in yellow.

performance increase for participants with a more External Locus of Control instead of those with a more Internal Locus of Control.

Notably, for the Dynamics Transfer, the difference in sign of the $LOC \times Stage[LTR]$ estimate between Groups is also reflected in a significant $LOC \times Stage[LTR] \times Group$ interaction effect. This shows that the Training methods (i.e. a participant's allocated Group) have significantly different effects on Performance increase from Baseline to Long-Term Retention depending on the Locus of Control ($p = 0.001$).

Since the Group and Baseline are taken as reference in our regression analyses, the fixed effects of LOC describe the slopes of the red regression lines per Group at Baseline. None of these fixed effects are significant, according to the LOC column in Table III, although the Dynamics Transfer shows a relatively high positive slope at Baseline for the Control Group in both the aforementioned Table and Figure.

B. Training Results

In Figure 5 the regression lines of Absolute Error and Absolute Interaction Force during Training are visualized. The results of the fixed effect of the Locus of Control and the Locus of Control interaction with the Training Set Index are presented in Table IV. The underlying data for the Experimental Group can be found Appendix K, Figures 21 and 22. This Appendix also contains Tables XIX, XX, and XXIII, containing the complete regression results for all three Training metrics.

Both Groups decreased their Absolute Error throughout Training, visible in Figure 5 and denoted by the significant negative estimates of the $trIndex$ fixed effects for this outcome metric ($p < 0.001$) in Tables XIX and XX. However, the decrease in Absolute Error during Training with Haptic Guidance was significantly greater for participants with a more Internal than External Locus of Control (Table IV: $trIndex \times LOC$, $p = 0.021$).

In this context, the positive estimate indicates that as Training progressed (higher $trIndex$), a gradual counter-clockwise rotation of the slope between Absolute Error and Locus of Control occurred, which is visible in Figure 5-B as well. However, at the start of Training, Absolute Error was (non-significantly) higher for people with a more Internal Locus of Control denoted by a negative estimate of LOC ($p = 0.603$).

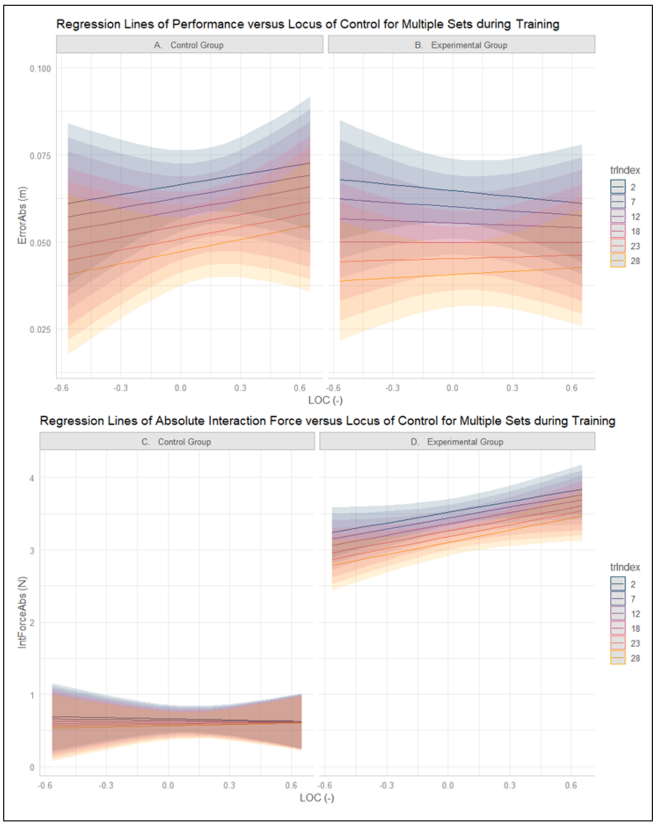

Fig. 5: Training regression lines of the $LOC*trIndex*Group$ term (Equation 8) of a selection of the Experimental Training Sets ($trIndex$), shaded with their 95% confidence interval. The first column shows the Control Group and the second column the Experimental Group of the outcome metrics $ErrorAbs$ **(A-B)**, and $IntForceAbs$ **(C-D)**.

The Control Group shows a non-significant positive estimate for LOC ($p = 0.559$), and this effect remains relatively constant throughout Training (estimate of $trIndex \times LOC$ is close to zero with $p = 0.666$), see Figure 5-A.

		LOC			LOC x trIndex		
Training Outcome Metric	**Group**	**Estimate**	**CI**	**p-Value**	**Estimate**	**CI**	**p-Value**
ErrorAbs (m)	C	0.00929	-0.02189 – 0.04048	0.559	0.00008	-0.00029 – 0.00046	0.666
	E	-0.00630	-0.03008 – 0.01747	0.603	0.00034	0.00005 – 0.00063	**0.021**
IntForceAbs (N)	C	-0.05552	-0.68044 – 0.56941	0.862	0.00396	-0.00272 – 0.01064	0.246
	E	0.48641	0.01001 – 0.96282	**0.045**	0.00269	-0.00240 – 0.00778	0.301
DevRefAbs (m)	C	-	-	-	-	-	-
	E	0.01004	0.00349 – 0.02357	0.146	0.00002	-0.00013 – 0.00017	0.798

TABLE IV: Locus of Control regression results for Training. A selection of the effects described by Formula 8 of the Performance ($ErrorAbs$) and Interaction ($IntForceAbs$ and $DevRefAbs$) outcome metrics. LOC denotes the fixed effect of Locus of Control on the reference, i.e. the corresponding Group and Training Set number 1, and $LOC \times trIndex$ the interaction effect between Locus of Control and Training Index. P-Values are determined through a two-sided t-Test with significant p-Values denoted in bold. Significant results related to the Locus of Control trait are highlighted in yellow.

The Absolute Interaction Force shows an effect that is opposite to the hypothesized direction in Hypothesis 2; the significantly positive estimate of LOC in Table IV ($p = 0.045$) on this outcome metric, represents less interaction with the Haptic Guidance method for participants with a more Internal than External Locus of Control in the Experimental Group. See Figure 5-D for a visualization. The phenomenon is accompanied by a (non-significantly) lower Deviation from the Reference of the Haptic Guidance in people with Internal compared to External Locus of Control, as denoted by the positive estimate of LOC in Table IV ($p = 0.146$).

Compared to Figure 5-C, it can be seen that the Interaction Force magnitude is lower in the Control Group, than the Experimental Group, represented by the relatively high negative estimate for $Group[C]$ in Table XX of Appendix K ($p < 0.001$). As expected, no significant effects of the Locus of Control were found on this outcome metric in the Control Group (Table IV).

C. User Experience Results

Task Experience: Figure 6 shows the regression lines of the two Sense of Agency questions. Regression results that include the LOC variable are presented in Table V. Appendix L contains the complete regression results in Tables XXV and XXVI, and a visualization of the underlying data in Figures 24 and 26. Appendix M contains the results with respect to Intrinsic Motivation.

In the Control Group, a statistically significant negative fixed effect of LOC is present for both Sense of Agency questions $AgencyControl$ ($p = 0.002$), and $AgencyCauseMovements$ ($p = 0.008$), representing a higher Sense of Agency at Baseline for Internal participants than External participants, which is also reflected in the negative $AgencyMean$ estimate ($p = 0.001$). The Experimental Group also shows a negative effect of LOC at baseline for the $AgencyCauseMovement$ question ($p = 0.064$), but exhibits positive, non-significant, effects for the LOC fixed effect for the $AgencyControl$ question.

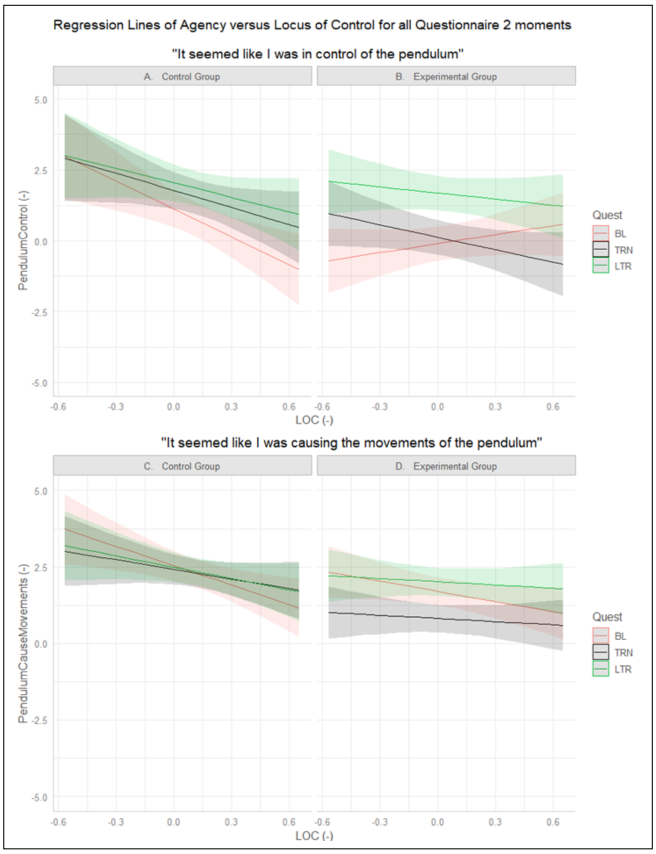

Fig. 6: User Experience regression lines of the $LOC * Quest * Group$ term (Equation 9) of the two Sense of Agency questions, shaded with their 95% confidence interval. **(A-B)** show $PendulumControl$ and **(C-D)** $PendulumCauseMovements$, with the Control Group left and the Experimental Group right.

The Experimental Group exhibits the expected decrease in Sense of Agency after collaboration with robotic-assistance in $MeanAgency$ with a (non-significant) negative estimate for $Quest[TRN]$ (Appendix L, Table XXVI). However, when regarding the questions separately, we find a significantly negative estimate for the same fixed effect ($p = 0.002$) in $AgencyCauseMovements$, whereas the $AgencyControl$ shows a non-significant positive estimate for the Experimental Group.

Surprisingly, the $AgencyControl$ variable shows an even higher change from Baseline to after Training in the Experimental Group than expected from Hypothesis 3, as the interaction effect $LOC \times Quest[TRN]$ suggests an increase in Sense of Agency for participants with a more Internal Locus of Control compared to External Locus of Control. In Figure 6-B this can be seen through the relative counter-clockwise

		LOC			LOC x Quest[TRN]			LOC x Quest[LTR]			LOC x Quest[TRN] x Group			LOC x Quest[LTR] x Group		
Sense of Agency	**Group**	**Estimate**	**CI**	**p-Value**	**Estimate**	**CI**	**p-Value**	**Estimate**	**CI**	**p-Value**	**Estimate**	**CI**	**p-Value**	**Estimate**	**CI**	**p-Value**
AgencyControl	C	-3.29	-5.35 – -1.23	**0.002**	1.28	-1.19 – 3.74	0.307	1.59	-0.87 – 4.05	0.204	-3.81	-6.91 – -0.71	**0.016**	-3.37	-6.47 – -0.28	**0.033**
	E	1.06	-0.51 – 2.63	0.183	-2.53	-4.41 – -0.65	**0.009**	-1.79	-3.66 – 0.09	0.062	3.81	0.71 – 6.91	**0.016**	3.37	0.28 – 6.47	**0.033**
Agency CauseMovements	C	-2.12	-3.66 – -0.57	**0.008**	1.06	-0.84 – 2.97	0.271	0.87	-1.04 – 2.78	0.367	-0.30	-2.70 – 2.09	0.803	-0.12	-2.51 – 2.28	0.924
	E	-1.11	-2.28 – 0.07	0.064	0.76	-0.69 – 2.21	0.302	0.75	-0.70 – 2.21	0.306	0.30	-2.09 – 2.70	0.803	0.12	-2.28 – 2.51	0.924
AgencyMean	C	-2.70	-4.24 – -1.16	**0.001**	1.17	-0.72 – 3.06	0.223	1.23	-0.66 – 3.12	0.200	-2.06	-4.44 – 0.32	0.090	-1.75	-4.13 – 0.63	0.149
	E	-0.02	-1.20 – 1.15	0.968	-0.89	-2.33 – 0.56	0.226	-0.52	-1.96 – 0.93	0.480	2.06	-0.32 – 4.44	0.090	1.75	-0.63 – 4.13	0.149

TABLE V: Locus of Control regression results for Sense of Agency. Selection of the effects described by Formula 9 of the $AgencyControl$, $AgencyCauseMovements$ question and the mean of the two questions. LOC denotes the fixed effect of Locus of Control on the reference, i.e. the corresponding Group and Baseline Questionnaire 2. $LOC \times Quest$ the interaction effect between Locus of Control and the Questionnaires after Training (TRN) and at Long-Term Retention (LTR). For each of these Stages, the interaction effect with $Group$ is shown as well. P-Values are determined through a two-sided t-Test with significant p-Values denoted in bold. Significant results related to the Locus of Control trait are highlighted in yellow.

rotation of the Baseline line (red) to the line after Training (black). This theory is supported by Figure 25 (Appendix L), where the individual difference in Sense of Agency of participants between their Baseline $AgencyControl$ and that after Training shows a Pearson correlation of $r = -0.440$ with Locus of Control ($p = 0.052$).

However, Intrinsic Motivation exhibits no significant effects of the Locus of Control variable. We refer the reader to Appendix M for more information, with the complete regression results in Tables XXIX and XXX.

Robot Experience: We found a significant correlation of 0.562 ($p = 0.0099$) between perceived Frustration from the robot collaboration with Haptic Guidance in the Experimental Group, representing lower Frustration in participants with a more Internal Locus of Control. On average, the Haptic Guidance was perceived as Helpful (mean of 0.35, std. dev. of 1.84) and Restricting (mean of -1.40, std. dev. of 0.99) as visualized in Figure 29 (Appendix N), together with further analyses and visualizations.

IV. Discussion

A. Motor Learning Discussion

1) ***Training with Haptic Guidance appears to enhance Motor Learning in individuals with a more Internal Locus of Control relatively more than with an External Locus of Control****:*
Krakauer interprets Motor Learning as a relatively permanent change in skilled behavior [58]. Our Motor Learning results, with respect to the Locus of Control and Training with Haptic Guidance, are both greater and more significant during Long-Term Retention compared to Short-Term Retention ($LOC \times Stage[LTR]$ versus $LOC \times Stage[STR]$). This finding aligns with Krakauer's concept of a relatively permanent change, as the results from the second, Long-Term, experimental session are even more pronounced. However, fatigue from the relatively long Training period before the Short-Term Retention, could have negatively affected the results from that Stage.

Moreover, our Motor Learning results are in line with those of Bragoni et al. [24], suggesting better Motor Learning for people with a more Internal Locus of Control than External Locus of Control in combination with Haptic Guidance, with a lower, non-statistically significant effect in the Control Group. This provides evidence for a better suitability of Haptic Guidance for individuals with a more Internal than External Locus of Control for Motor Learning.

Bragoni et al. used a clinical outcome measure for walking ability [59], and a Locus of Control scale specifically designed for recovery from stroke [26]. Our study indicates that the influence of Locus of Control, in combination with Haptic Guidance Training, extends to a broader Locus of Control scale, which is not specifically focused on recovery [33]. Furthermore, this effect is observed even when learning a substantially different, i.e. walking versus target hitting, and using Haptic Guidance for the upper-, instead of lower-limb. Both their and our study only consisted of 42 participants, and even then provided statistically significant results, further substantiating the possible positive effect on Motor Learning of a more Internal Locus of Control in combination with Haptic Guidance Training.

2) ***Training with Haptic Guidance suggest superior Generalization of Motor Learning in individuals with a more Internal rather than External Locus of Control, with a smaller or even opposite effect after Training without Haptic Guidance****:*
According to Magill & Anderson, when well-chosen Transfer Tasks are selected, Generalization of Motor Learning to these Tasks provides the best assessment, as those can be designed to fit the situations for which the practice was intended [60]. In our study, the Transfer Tasks were either designed to contain a target pattern with higher nominal difficulty than the Main Task, or to evaluate the adaptation to more reactive Pendulum Dynamics (see Appendix D).

For both these Tasks, our Target Transfer and Dynamics Transfer results suggest a relatively permanent better Generalization of Motor Learning in people with a more Internal than External Locus of Control after Training with Haptic Guidance. When these effects were compared to Training without Haptic Guidance, they were non-significantly lower (Target Transfer), or even significantly lower (Dynamics Transfer). Therefore, these findings again support the notion that Haptic Guidance is more suited for individuals with

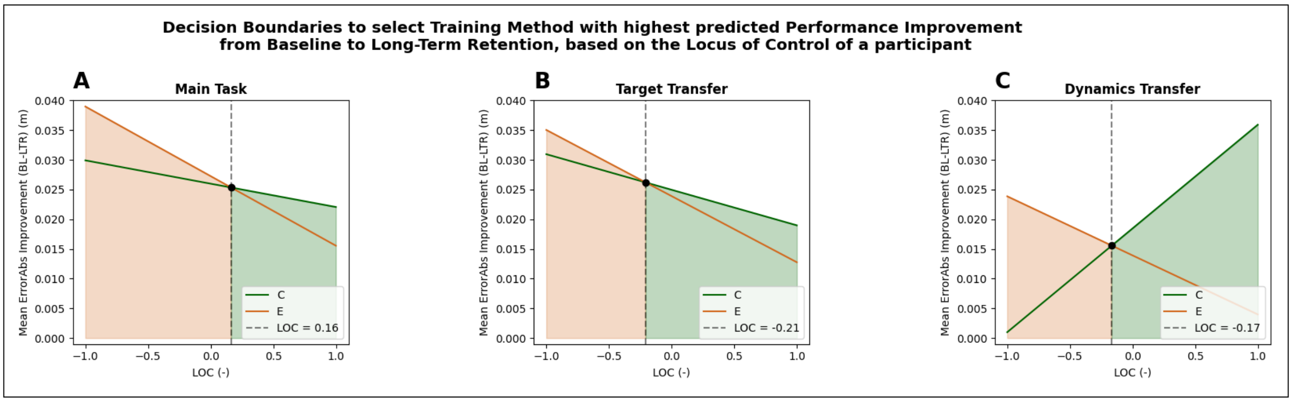

Fig. 7: Mean improvement of assessment test targets from Baseline to Long-Term Retention, based on the Locus of Control for the **(A)** Main Task, **(B)** Target Transfer and **(C)** Dynamics Transfer. The optimization from Equation 11 is visualized per Group, resulting in the green- (Control Group) and orange line (Experimental Group). Greedy selection of the Training Strategy with the highest predicted improvement leads to the shaded planes in a lighter color of the corresponding Group. The Locus of Control value, denoted with the dashed line, represents the decision boundary between the two Training Strategies. The lines in **A** and **B** display exclusively negative slopes, which signifies a comparatively greater enhancement in performance for individuals with a more Internal Locus of Control, regardless of the Training Strategy. This is in line with Section IV-A3, as well as the opposite effect in the Control Group in **C** indicated by the positive slope of the corresponding line.

a stronger Internal rather than External Locus of Control. Furthermore, these results differ from those of Bragoni et al. [24], who did not observe any effect of Locus of Control of Recovery on their secondary outcome measure. They assessed improvements in activities of daily living [61], and we believe that the discrepancy between our findings can be attributed to the activities of daily living being less similar to the Trained Task compared to the Main and Transfer Tasks used in our study.

*3) **Regardless of the Training method, an Internal rather than External Locus of Control suggests consistently higher Motor Learning in the Pendulum Game and Generalization of Learning to a more difficult target pattern, but not for Generalization to altered Pendulum Dynamics**:* The Control Groups for the Main Task and Target Transfer displayed in Figure 4, indicate a similar trend of relatively better Long-Term performance improvement in people with a more Internal rather than External Locus of Control, although both with statistically insignificant effects of lower magnitude (Table III). This effect was further confirmed after fitting a model per Task, without considering the $Group$ variable, based on Equation 7.

The results of these models are presented in Table XV (Appendix H). The interaction effects between Locus of Control and $Stage[LTR]$ are found to be significantly positive (with respective p-values of 0.048 and 0.032), for both the Main Task and Target Transfer. This suggests that, independent of the Training method, a more Internal Locus of Control is better suited for Motor Learning and Generalization of Motor Learning in the Pendulum Game than a more External Locus of Control. However, the magnitudes of these effects are comparatively smaller than their corresponding effects observed in the Experimental Group, suggesting that an Internal Locus of Control character trait is *even better suited* for Training with Haptic Guidance, than without, which is in line with our research question. Additionally, this effect does not generalize to the Dynamics Transfer, where instead a more External rather than Internal Locus of Control shows higher Generalization of Motor Learning in the Control Group.

The reason for a general positive effect of Locus of Control could be due to other aspects important to Motor Learning, such as its effect on the Flow state, which is known to entail high focus and performance [62]. People with an Internal Locus of Control tend to enter and/or stay in the Flow state better than External oriented people when presented with a task where their skill level was not balanced with their perception of the task difficulty, which may occur in our experiment [63].

*4) **Based on our findings, we developed a method to select the Training Method potentially leading to relatively higher Long-Term performance improvements for new participants, determined by their Locus of Control**:* The Motor Learning models developed in this study, visualized in Figure 4, can be used to select the Training method that is estimated to lead to the best Motor Learning outcomes for one of our three Tasks for a new participant, based on their Locus of Control.

$$TrainingStrategy^*_{Task} = \arg\max_{Group} \frac{1}{40} \Big(\sum_{sIndex=0}^{1} \sum_{wIndex=0}^{19} \big(Err\hat{or}Abs(LOC, Group, Stage = BL) - Err\hat{or}Abs(LOC, Group, Stage = LTR) \big) \Big) \tag{11}$$

We propose to greedily select the predicted optimal Training Strategy for the desired Task ($TrainingStrategy^*_{Task}$), i.e. an allocation to a $Group$, with the highest predicted increase in Absolute Error for all 2 sets of 20 Targets from Baseline to Long-Term Retention, through Equation 11. This approach is based on Gerig et al. [18].

In Figure 7, the underlying selection method of Equation 11 is visualized. In this Figure, it can again be seen that the effect of Locus of Control on the relative difference in performance improvement between the two Groups, is smaller in the Main Task and Target Transfer than the Dynamics Transfer. This is demonstrated by the lines representing the improvement in performance per Group, crossing each other with a larger angle in the Dynamics Transfer Task, compared to the other Tasks. In our regression results, this phenomenon is described by a lower $LOC \times Stage[LTR] \times Group$ interaction effect for the first two Tasks than the Dynamics Transfer, with the effect being highly significant in the Dynamics Transfer ($p = 0.001$).

Therefore, from all the Tasks, we expect that using the decision boundary from the Dynamics Transfer for Training Strategy assignment, would result in the most pronounced differences in Generalization of Motor Learning between Training Strategies. Through this, the overall lower effectiveness of the Haptic Guidance Training in the Target Transfer (Section III-A1) might even be counteracted.

To validate whether an allocation to a Training Strategy, based on Equation 11, is in fact the optimal allocation for new participants, an experiment similar to the one from Rauter et al. [17] can be performed. A New Experimental Group can be created in which participants are assigned to the Training Strategy according to Equation 11. The New Control Group is then randomly allocated to a Training Strategy. Better results in (Generalization of) Motor Learning for the New Experimental Group compared to the Control Group would then support the use of our method.

B. Training Discussion

1) ***Variations in Task Objectives and Robot-Assistance characteristics might be the cause of contrasts with prior literature in observed Haptic Guidance interactions****:* Contrary to our expectations (Hypothesis 2), participants with a more Internal Locus of Control exhibit less interaction with the Haptic Guidance strategy than those with a more External Locus of Control. This is evident not only in the lower Absolute Interaction Force, as indicated by the positive estimate of the LOC fixed effect ($p = 0.045$) for this Group, resulting in decreased Deviation from the Reference Trajectory for individuals with a more Internal Locus of Control ($p = 0.146$) (visualized in Figure 20 in Appendix K).

These outcomes appear contrary to prior research [27] [28] [29]. However, all these prior studies involved obstacle avoidance tasks, where the robot-assistance consisted of forces repelling the user from these obstacles. Our Pendulum Game, on the other hand, involved Target hitting. This led to the design of robot-assistance forces guiding the participant to a reference trajectory primarily designed for guiding towards these Targets (see Appendix A). Similarly, the robot-assistance strategy employed by Bragoni et al. [24], guided the feet of participants towards an optimal gait pattern, which seems to be more similar to the objective of our task. It appears that our results therefore depend on the type of Task and implementation of Haptic Guidance, and is further substantiated by prior research indicating that Haptic Guidance efficacy depends on the task characteristics [5].

2) ***Enhanced (Generalization of) Motor Learning observed in individuals with a more Internal Locus of Control after Training with Haptic Guidance, could be due to higher functional effort, better perception of the pendulum dynamics and/or better adaptation to the strategy****:* We expected that higher interaction during Training could lead to relatively higher Motor Learning results for individuals due to higher effort and engagement. However, the higher interaction was found in more External participants, who have instead shown *less* (Generalization of) Motor Learning after Haptic Guidance than more Internal participants, as discussed in Section IV-A1 and A2. This leads us to speculate about other factors that could cause the observed differences in (Generalization of) Motor Learning after Haptic Guidance, for which we see three potential explanations.

The relatively lower interaction force with Haptic Guidance in participants with an Internal Locus of Control may instead represent higher functional effort: Prior research has shown conflicting results for the efficacy of Haptic Guidance in healthy individuals [3] [5]. In Section I-A we mentioned Haptic Guidance potentially hampering motor learning through the slacking effect, causing lower effort and engagement, factors necessary for motor learning [21] [22] [64]. We expected that a lower interaction force with the robot, would represent a higher dependence on the assistance for correct Task Performance. However, based on further analyses, we believe that the reduced interaction forces, observed in participants with a more internal Locus of Control, actually signify a higher level of *functional effort* during Training, through the following reasoning.

In order to hit targets with the pendulum, forces should be applied to its end-effector to move the inherent swinging pattern of the pendulum, in a controlled manner, out of its natural frequency [25]. Our Haptic Guidance strategy is designed to do this (see Appendix A), and indeed additional analyses show that, on average, the (collaborative) movement of the end-effector with Haptic Guidance results in the pendulum swinging more out of its natural frequency in the Experimental Group, compared to the Control Group. This is denoted by the highly negative and significant estimate of -13.22 ($p = 0.0002$) for the corresponding $\omega_N\%PSD$ comparison in Table XVIII (Appendix J). We refer the reader to Appendix F for a further explanation of this metric.

A lower $\omega_N\%PSD$ corresponds to the pendulum swinging more outside its natural frequency, which correlates with performance in the Pendulum Game [25] [39]. Participants with a more Internal Locus of Control, swing the Pendulum more out of its natural frequency during Training, compared to more External participants. This is visible in Figure 33, and denoted by the positive fixed effect of LOC ($p = 0.072$) in the corresponding Table XL, both in Appendix O.

Thus, on average, participants with a more Internal Locus of Control seem to exhibit a higher, more useful, effect on the Pendulum swing motion when Training with Haptic Guidance, accompanied by a lower interaction force with the Haptic Guidance. We believe that the only way this can occur, is through exerting forces more in line with those applied by the Haptic Guidance. This suggests that these individuals are causing the higher effect on the Pendulum swing, through a more effective, and thus *functional*, effort during Training. Individuals with a more External Locus of Control, seem to exhibit effort that opposes the Haptic Guidance strategy relatively more. This both may result in their combination of relatively higher interaction forces, accompanied by less functional effects on the Pendulum swing motion (i.e. higher $\omega_N\%PSD$).

Moreover, the reduced opposing forces experienced during training may have contributed to the decreased perceived Frustration associated with the interaction in these individuals, aligning with the rationale presented by Acharya et al. [28]. Both this relatively lower frustration and the more effective application of effort, might have contributed to the positive effects on our Motor Learning outcomes [3] [64], for individuals with a more Internal Locus of Control.

There might be a better perception of the Pendulum dynamics in participants with a more Internal Locus of Control through a lower Absolute Interaction Force: Another issue of Haptic Guidance is its effect on the perceived Task dynamics for participants. During practice without Haptic Guidance, movements produce force feedback that correspond to the inherent dynamics of the Task through the Haptic Rendering [5]. However, during Training with Haptic Guidance, identical movements yield force feedback influenced by both the task dynamics and the applied guidance forces [5]. This can lead to the human learning task dynamics that are not representative of the original task, hampering their improvement [65] [5].

Our results show a significantly higher Absolute Interaction Force in the Experimental Group than the Control Group ($p < 0.001$). However, this effect was significantly less strong in participants with a more Internal Locus of Control ($p < 0.045$). This suggests a lower negative effect on the perception of task dynamics for individuals with a more Internal Locus of Control, potentially contributing to their comparatively higher (Generalization of) Motor Learning to more External individuals after Training with Haptic Guidance.

Individuals with a more Internal Locus of Control might adapt Better to Haptic Guidance strategy: When taking the Locus of Control into account, participants with a more internal Locus of Control show significantly more performance improvement throughout Training ($p = 0.021$). Thus, participants with a more Internal Locus of Control might adapt to the Haptic Guidance throughout Training in a way that leads to a more fruitful collaboration.

Their improvement during Training might have contributed to the lower Frustration perceived by these individuals. Prior achievements serve as a basis for developing confidence or self-efficacy, which, according to the OPTIMAL theory [21] [22], can contribute to enhanced Motor Learning outcomes. This could then contribute to the relatively higher (Generalization of) Motor Learning in individuals with a more Internal rather than External Locus of Control.

3) ***Participants with an External Locus of Control might exhibit better suited training behavior for learning the Pendulum dynamics when training without Haptic Guidance****:*
In the Control Group, participants with a more External Locus of Control seem to exhibit increasingly more variable movements of the end-effector throughout Training (Figure 31-A, Appendix O). In the same Group, a more Internal Locus of Control exhibits less variable end-effector movements, which remain relatively constant throughout training. However, these different types of end-effector movement, lead to increased, useful effects on movement of the pendulum out of the natural frequency regardless of Locus of Control (see Figure 32-A, visualizing the significant ($p < 0.001$) negative $trIndex$ fixed effect). Additionally, regardless of Locus of Control, increasing performance throughout Training is present (Figure 5-A, visualizing the significant $trIndex$ fixed effect ($p = 0.001$) from Table XIX). This suggests differences in training strategies (either more or less variable movements), depending on the Locus of Control, that are both effective in moving the pendulum out of the natural frequency.

However, the presence of more variable movements in the more External individuals, potentially enables them to understand the pendulum's response to such variations better. This approach could be a superior training method for the Dynamics Transfer Task, given the high responsiveness of the pendulum to the end-effector's movements for this task specifically.

Then, participants with a more Internal Locus of Control are, in turn, less prepared for the Dynamics Transfer in the Control Group. Indeed, their Long-Term improvement in this Task is relatively lower than in more External participants when training without Haptic Guidance, as visible in Figure 4-E. Note that the relatively lower initial skill level in more External participants could have inflated these results, as a lower initial skill level allows a greater potential for improvement [3].

4) ***Participants with an External Locus of Control might be hampered by the Haptic Guidance****:*
In Section IV-B2, we discussed that the behavior of the more Internal Locus of Control could be more in line with that of the Haptic Guidance, suggesting a better perception of the pendulum dynamics relatively better when training with it, compared to the more External Locus of Control. This is supported by their relatively higher Long-Term performance improvement, visible in Figure 4-F.

The more Internal behavior seems to be less effective for the Dynamics Transfer Task than the more External behavior, as discussed in Section IV-B3. However, it seems that for more External individuals, their "superior" learning strategy for the Dynamics Transfer is hampered through the Haptic Guidance, as they might be actively resisting it through the relatively higher interaction force.

This, in turn, would explain the significantly lower effectiveness of Haptic Guidance for the learning of the Dynamics Transfer for the Experimental Group as a whole, which is denoted in Table II.

C. User Experience Discussion

1) ***The relative increase in perceived Pendulum control for people with a more Internal Locus of Control can contribute to the observed differences in (Generalization of) Motor Learning after Training with Haptic Guidance:***
When examining the extent to which participants felt in control over the Pendulum, an even stronger effect than we anticipated in Hypothesis 3 was observed, after Training with Haptic Guidance. Participants with a more internal Locus of Control tend to show an increase, while those with a more External showed a decrease in their Sense of Control compared to Baseline ($p = 0.052$), instead of the hypothesized relatively lower decrease.

We believe that the relatively greater motor learning observed in individuals with an Internal Locus of Control when using Haptic Guidance, could be –partially– attributed to this perception of being more in control despite the Haptic Guidance taking over control, through restricting the participant in their own intended movement. This seems to be in line with the definition of Internal vs. External Locus of Control presented in Section I-G.

Perceived control during training has shown to influence motor learning outcomes, when for example choosing how many basketball shots to take during practice [66], or even providing a choice between seemingly irrelevant options such as golf ball color [67]. It could be that a similar mechanism is at work here, which may contribute to the comparatively higher level of (Generalization in) Motor Learning in individuals with a more Internal rather than an External Locus of Control.

2) ***In line with prior research, most of our results indicate a higher Sense of Agency for more Internal than External individuals:***
Prior research presented correlations between Sense of Agency and a more Internal Locus of Control [31] [30], displaying a general higher Sense of Agency for people with a more Internal Locus of Control. Whereas this prior research only investigated Sense of Agency with a question regarding perceived control, our results indicate that this effect generalizes to a question regarding perceived cause of movements as well.

Almost all our results from the two Agency questions display this phenomenon, through negative estimates of the LOC fixed effect. Only for the $AgencyControl$ question, this initial effect is non-significantly opposite. This might contribute to the larger observed effect after training for this question than expected, (see Section IV-C1), as initially a higher perceived control would have been expected for individuals with a more Internal Locus of Control than is currently present.

3) ***Intrinsic Motivation was not significantly affected by the Locus of Control:***
Wulf and Lewthwaite named the concept of perceived control over Training conditions "autonomy", which has been shown to positively influence Intrinsic Motivation [21] [22].

More Internal individuals both exhibit an increase in perceived Pendulum control after training with Haptic Guidance, and a relatively higher level of frustration regarding Haptic Guidance interaction compared to more External individuals. One would expect this to lead to relatively higher improvement of Intrinsic Motivation in the former individuals. However, we only found (non-significant) evidence supporting this notion through the negative interaction effects between LOC and both $Quest[TRN]$ and $Quest[LTR]$ for the $PerceivedCompetence$ subscale of the Intrinsic Motivation Inventory in Table XXX (Appendix M).

Participants in the Experimental Group may interpret the questions from the Intrinsic Motivation Inventory, which revolve around the rather vaguely described "activity", to refer only to the hitting of targets, instead of encompassing both the pendulum movements (Sense of Agency) and Robot Interaction as well. The Intrinsic Motivation Inventory might either not accurately measure the effects of these aspects on participants' Intrinsic Motivation, or the observed effects are simply not enough to affect their Intrinsic Motivation. Another option may be that the relatively high variance present in the results from the Intrinsic Motivation Inventory, are due to other factors, potentially resulting from other traits of the individuals.

This is further supported by the (non-significant) comparatively greater decrease in $Interest/Enjoyment$ after Training with Haptic Guidance compared to Baseline for more Internal participants in the Experimental Group (indicated by the positive estimate of $Quest[TRN]$ in Table XXX), representing an unexpected higher decrease in $Interest/Enjoyment$ of the activity for participants with a more Internal Locus of Control.

D. Locus of Control Discussion

1) ***The observed effects related to Motor Learning, Training, and User Experience may stem from individuals' inherent beliefs, according to their Locus of Control:***
Individuals with a highly Internal Locus of Control, have an intrinsic belief that they are in control over the outcomes that result from their actions. In this study, we have seen that their perception of being in control indeed is not negatively impacted by the potential loss of control due to the Haptic Guidance forces (see Section IV-C1).

We hypothesize that the observed lower interaction force and reduced variability in end-effector movements (Section IV-B) during collaboration with Haptic Guidance can be attributed to this perceptual difference in individuals with a more Internal Locus of Control, compared to those with a more External Locus of Control.

Individuals with a more Internal Locus of Control may experience a lower necessity to gain back control over the Pendulum through, for example, opposing the Haptic Guidance or exhibition of more variable end-effector movements.

Indeed, these phenomenons were observed more in individuals with an increasingly External Locus of Control. As such, further observed differences resulting from training with Haptic Guidance, e.g. in Motor Learning outcomes and perceived Frustration, may all stem from this inherent disparity in beliefs.

E. Recommendations

In this research, we have refrained from using corrections for multiple comparisons in the regression models. Due to our relatively low statistical power, resulting from the small number of participants in our research, the risk of Type II errors would have been high. Nonetheless, we accompany all our main regression result Tables with their corrected counterparts through the False Discovery Rate [56] in the Appendix. We strongly advise on the use of a larger sample size in follow-up studies.

Furthermore, we recommend presenting the Control Group the Robot Interaction Experience questions as well, by making all participants explicitly aware of the Haptic Rendering. The Control Group would then provide their perceptions regarding this interaction, instead of the Haptic Guidance. This would mainly be useful for further investigation of the observed differences in perceived Frustration.

F. Future Research

We identify two main directions for future research based on this study; one that involves a focus on further investigation of the Locus of Control trait itself, and the other a focus on the practical use of the trait for the selection of a better suited training strategy for an individual for motor learning. A first step for the latter direction has been made in Section IV-A4, and could be made more powerful through further research on, and potential combination with, other user characteristics, such as the Autotelic Personality Trait [44] or a person's preferred Gaming Style [43].

Further research on the Locus of Control with respect to robot-assisted motor learning, could start with an investigation of more accurately pinpointing what specific aspect of the Locus of Control trait could be the most influential, for example by using a questionnaire that separates the Locus of Control into three lower level components, Internal, Powerful Others and Chance [68]. The use of a Dynamics Transfer with a longer instead of shorter Pendulum could give new insights as well.

Additionally, more research should be performed to investigate robot-assistance strategies that are more accommodating for the beliefs and perceptions of individuals with a more External Locus of Control. Methods with highly different working mechanism, such as error amplification [7] or haptic noise [39] could be of potential interest.

In our study, we attempted to explain the observed motor learning effects by examining training behavior and –potentially associated– changes in user experience, based on the Locus of Control. However, our findings could also be of use in research fields where Motor Learning is of less concern. For example, the Locus of Control could potentially aid in adapting haptic guidance driver support systems [69] to the user, considering its influence on user experience and behavior during collaborative performance.

V. Conclusion

In this study, we have found evidence of superior (Generalization of) Motor Learning when Training with Haptic Guidance for individuals with a more Internal rather than External Locus of Control. We argued that this could be due to observed differences in training behavior, where participants with a more Internal Locus of Control exhibit more performance improvement and lower interaction force during collaborative training with Haptic Guidance.

Furthermore, we proposed that observed differences in self-reported User Experience could have also contributed to this superior (Generalization of) Motor Learning. They consisted of an increase, as opposed to a decrease, of the perception of control over the Pendulum after training with Haptic Guidance in more Internal individuals, as well as a lower frustration related to the Haptic Guidance interaction.

We hypothesized that the intrinsic belief disparity of individuals according to their Locus of Control might be the origin of differences in training behavior, resulting in the observed Motor Learning outcomes. Compared to training without Haptic Guidance, the magnitude of these differences for the (Generalization) of Motor Learning depend highly on the task characteristics. Specifically for a task with different pendulum dynamics, Haptic Guidance might even hamper individuals with a more External Locus of Control.

We conclude that Haptic Guidance seems better suited for individuals with a more internal rather than External Locus of Control, not only in motor learning, but also during training and with respect to their user experience.

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APPENDIX A
HAPTIC GUIDANCE

A. Trajectory Optimization

With the quadratic cost function formulation from the ACADO toolkit [40], the following convex and smooth cost function was obtained:

$$J(x,u) = \sum_{k=t_0}^{t_0+N-1} h(x_k,u_k)^\top W h(x_k,u_k) + h_{t_0+N}(x_{t_0+N})^\top W_{t_0+N} h_{t_0+N}(x_{t_0+N}). \tag{12}$$

Here t is the initial time step, N the horizon length, W the cost matrix for all time steps except for the terminal state x_{t_0+N}, which has its own cost matrix W_{t+N}. The functions $h(x_k,u_k)$, depending on the state x_k and action u_k, and h_{t_0+N} only depending on the terminal state x_{t_0+N}, are the stage cost function and the terminal cost function respectively. The states and actions in these functions are what will be optimized for.

In order to obtain the task specific optimization, the variables in the function are altered to the current task, as shown in [25]. The initial time-step t_0 is selected to be exactly one second before the next wall is hit. This next wall hit occurs at the terminal time step $t+N$.

The stage cost-function then has the following form:

$$h(x_k,u_k) = \begin{bmatrix} y_k + l\sin(\theta_k) \\ z_k - l\cos(\theta_k) \\ \dot{y}_k + l\dot{\theta}_k\cos(\theta_k) \\ \dot{z}_k + l\dot{\theta}_k\sin(\theta_k) \\ F_y \\ F_z \end{bmatrix}. \tag{13}$$

Here the first four rows describe the state of the Ball at time step k in terms of the End-Effector position and velocity in y- and z-direction. The last two rows describe the action, i.e. the force to apply to the End-Effector by a control system, at time step k to change the dynamic system.

The terminal cost-function only consists of the terminal state, as in principle no more changes to the dynamic system are needed after the terminal state for the current optimization round. The terminal cost-function is described as follows:

$$h_{t_0+N}(x_{t_0+N},u_{t_0+N}) = \begin{bmatrix} y_{t_0+N} + l\sin(\theta_{t_0+N}) - y_{\text{target}} \\ z_{t_0+N} - l\cos(\theta_{t_0+N}) \\ \dot{y}_{t_0+N} + l\dot{\theta}_{t_0+N}\cos(\theta_{t_0+N}) \\ \dot{z}_{t_0+N} + l\dot{\theta}_{t_0+N}\sin(\theta_{t_0+N}) \end{bmatrix} \tag{14}$$

B. Tuning the Reference Trajectory

By changing the weights in the W (15) and W_{t_0+N} (16) matrix of the cost-function, used in the trajectory optimization (Equation 12) we tune the reference trajectory to our desires.

$$W = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & Q_{\text{vy}} & 0 & 0 & 0 \\ 0 & 0 & 0 & Q_{\text{vz}} & 0 & 0 \\ 0 & 0 & 0 & 0 & R_y & 0 \\ 0 & 0 & 0 & 0 & 0 & R_z \end{bmatrix} \tag{15}$$

$$W_{t_0+N} = \begin{bmatrix} Q_{\text{target}} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & Q_{\text{vy}} & 0 \\ 0 & 0 & 0 & Q_{\text{vy}} \end{bmatrix} \tag{16}$$

Desired characteristics of the Haptic Guidance strategy are:

- *Stabilization of the Ball.* We penalize the velocity components of the Ball, by applying a weight of 40.0 to Q_{vy} and Q_{vz}, both in W and W_{t+N}, to avoid unstable behavior due to high angular velocity.
- *Comfortable Human Robot Interaction.* The hypothetical forces that are used to in the optimization to move the Pendulum should are penalized. Failure to do so, would result in trajectories that demand high end-effector accelerations to allow accurate guidance. This could lead to discomfort during Human-Robot Interaction. Therefore, we applied a linearly

decreasing weight R_y from 0.100 at time step t to 0.050 at the terminal time step, allowing higher support closer to the target [25].

- *Achieving high task performance*. The main objective of the Pendulum Game is to accurately hit targets. The first row of the terminal cost-function h_{t+N}, denotes the deviation from the target when an upcoming wall is hit. Therefore, a relatively large cost of 800 is attributed to the first diagonal entry, Q_{target}, of the cost matrix W_{t+N}, penalizing this deviation. No z-position target is tracked, so the corresponding entry is kept at 0.

The optimization is constrained to 81 time steps ($k = 80$ and 1 terminal time step). The chosen limit ensures that the optimization can be executed effectively in real-time. From the resulting states, the y-values are obtained, and fitted to a cubic b-spline to obtain a smooth reference trajectory (y_{ref}) for time steps at the system frequency of 1.67 kHz for the End-Effector.

C. Enforcing the Reference Trajectory

The resulting Haptic Guidance Force (F_{HG}) in y-direction is determined by a PD-controller according to Equation 6.

The error is represented by the difference between y_{ee} and y_{ref} at time step t for the We wanted to accommodate users with some possibility to deviate from the reference trajectory, to allow active engagement during the task (relatively lower K_p). Simultaneously, deviation from the reference presents a risk of unstable behavior of the Pendulum, as the trajectory is only updated once per target. Deviation can be counteracted with a higher K_p, in combination with a suitable K_d. Our reference trajectory was intentionally designed for an intrinsic stabilization of the ball, which we combined with values for K_p and K_d of 75.0 N/m and 15.0 N respectively.

Note that directly using the hypothetical forces of the optimization method, instead of the use of this PD-controller, would not allow Human-Robot Interaction, as the resulting controller would be similar to an open-loop version of a Linear Quadratic Regulator, which does not account for any deviation from the predicted states due to human behavior.

APPENDIX B
ROTTER'S LOCUS OF CONTROL SCALE

Rotter's Locus of Control Scale

For each question select the statement that you agree with the most

1. a. Children get into trouble because their patents punish them too much.

b. The trouble with most children nowadays is that their parents are too easy with them.

2. a. Many of the unhappy things in people's lives are partly due to bad luck.

b. People's misfortunes result from the mistakes they make.

3. a. One of the major reasons why we have wars is because people don't take enough interest in politics.

b. There will always be wars, no matter how hard people try to prevent them.

4. a. In the long run people get the respect they deserve in this world

b. Unfortunately, an individual's worth often passes unrecognized no matter how hard he tries

5. a. The idea that teachers are unfair to students is nonsense.

b. Most students don't realize the extent to which their grades are influenced by accidental happenings.

6. a. Without the right breaks one cannot be an effective leader.

b. Capable people who fail to become leaders hive not taken advantage of their opportunities.

7. a. No matter how hard you try some people just don't like you.

b. People who can't get others to like them don't understand how to get along with others.

8. a. Heredity plays the major role in determining one's personality

b. It is one's experiences in life which determine what they're like.

9. a. I have often found that what is going to happen will happen.

b. Trusting to fate has never turned out as well for me as making a decision to take a definite course of action.

10. a. In the case of the well prepared student there is rarely if ever such a thing as an unfair test.

b. Many times exam questions tend to be so unrelated to course work that studying in really useless.

11. a. Becoming a success is a matter of hard work, luck has little or nothing to do with it.

b. Getting a good job depends mainly on being in the right place at the right time.

12. a. The average citizen can have an influence in government decisions.

b. This world is run by the few people in power, and there is not much the little guy can do about it.

13. a. When I make plans, I am almost certain that I can make them work.

b. It is not always wise to plan too far ahead because many things turn out to- be a matter of good or bad fortune anyhow.

14. a. There are certain people who are just no good.

b. There is some good in everybody.

15. a. In my case getting what I want has little or nothing to do with luck.

b. Many times we might just as well decide what to do by flipping a coin.

16. a. Who gets to be the boss often depends on who was lucky enough to be in the right place first.

b. Getting people to do the right thing depends upon ability. Luck has little or nothing to do with it.

17. a. As far as world affairs are concerned, most of us are the victims of forces we can neither understand, nor control.

b. By taking an active part in political and social affairs the people can control world events.

18. a. Most people don't realize the extent to which their lives are controlled by accidental happenings.

b. There really is no such thing as "luck."

19. a. One should always be willing to admit mistakes.

b. It is usually best to cover up one's mistakes.

20. a. It is hard to know whether or not a person really likes you.

b. How many friends you have depends upon how nice a person you are.

21. a. In the long run the bad things that happen to us are balanced by the good ones.

b. Most misfortunes are the result of lack of ability, ignorance, laziness, or all three.

22. a. With enough effort we can wipe out political corruption.

b. It is difficult for people to have much control over the things politicians do in office.

23. a. Sometimes I can't understand how teachers arrive at the grades they give.

b. There is a direct connection between how hard 1 study and the grades I get.

24. a. A good leader expects people to decide for themselves what they should do.

b. A good leader makes it clear to everybody what their jobs are.

25. a. Many times I feel that I have little influence over the things that happen to me.

b. It is impossible for me to believe that chance or luck plays an important role in my life.

26. a. People are lonely because they don't try to be friendly.

b. There's not much use in trying too hard to please people, if they like you, they like you.

27. a. There is too much emphasis on athletics in high school.

b. Team sports are an excellent way to build character.

28. a. What happens to me is my own doing.

b. Sometimes I feel that I don't have enough control over the direction my life is taking.

29. a. Most of the time I can't understand why politicians behave the way they do.

b. In the long run the people are responsible for bad government on a national as well as on a local level.

Score one point for each of the following:

2. a, 3.b, 4.b, 5.b, 6.a, 7.a, 9.a, 10.b, 11.b, 12.b, 13.b, 15.b, 16.a, 17.a, 18.a, 20.a,

21. a, 22.b, 23.a, 25.a, 26.b, 28.b, 29.a.

A high score = External Locus of Control

A low score = Internal Locus of Control

Appendix C
Questionnaire 2 – Sense of Agency & Intrinsic Motivation

Default Question Block

Participant ID:

	strongly disagree -3	-2	-1	0	1	2	strongly agree 3
It seemed like I was in control of the pendulum.	○	○	○	○	○	○	○
It seemed like I was causing the movements of the pendulum.	○	○	○	○	○	○	○

	not at all true 1	2	3	somewhat true 4	5	6	very true 7
I thought this activity was quite enjoyable.	○	○	○	○	○	○	○
I tried very hard on this activity.	○	○	○	○	○	○	○
I felt pressure while doing the task.	○	○	○	○	○	○	○
I was pretty skilled at this activity.	○	○	○	○	○	○	○

	not at all true 1	2	3	somewhat true 4	5	6	very true 7
It was important to me to do well at this task.	○	○	○	○	○	○	○
I was anxious while working on this task.	○	○	○	○	○	○	○
The task was fun to do.	○	○	○	○	○	○	○

	not at all true			somewhat true			very true
	1	2	3	4	5	6	7
I put a lot of effort into this.	○	○	○	○	○	○	○

	not at all true			somewhat true			very true
	1	2	3	4	5	6	7
I am satisfied with my performance at this task.	○	○	○	○	○	○	○
I would describe this activity as very interesting.	○	○	○	○	○	○	○
I think I am pretty good at this activity.	○	○	○	○	○	○	○
I felt very tense while doing this activity.	○	○	○	○	○	○	○
I thought this was a boring activity.	○	○	○	○	○	○	○

APPENDIX D
TARGET LOCATIONS & NOMINAL TASK DIFFICULTY

TABLE VI: Target Locations: Main Task

	wIndex									
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Target x-position (m)	-0.12	-0.12	0.12	0.00	0.12	-0.12	0.12	-0.12	-0.12	0.00
	10	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**
Target x-position (m)	-0.12	0.00	0.12	-0.12	0.12	0.12	-0.12	0.00	-0.12	0.12

Within each set of the Main Task (Table VI), the first 4 targets are located with a relatively undemanding pattern, based on [39], starting with two subsequent locations at the start of the set, when the pendulum is (close to) its equilibrium state. From target index 4 to target index 8, participants are presented a challenging pattern, where first a high pendulum end-effector amplitude is necessary to obtain a high score (index 4-6), potentially resulting in a high amplitude of the internal degree of freedom of the pendulum (θ), after which two targets are positioned at the same lateral location (index 7-8) [39]. In the rest of the targets also two laterally identically positioned targets occur twice, however, the preceding distance between targets is less extreme than that from index 4-6.

TABLE VII: Target Locations: Target Transfer

	wIndex									
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Target x-position (m)	-0.12	0.12	0.12	-0.12	0.00	0.00	-0.12	0.12	-0.12	-0.12
	10	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**
Target x-position (m)	0.12	0.00	0.00	0.12	-0.12	-0.12	0.12	-0.12	0.00	0.00

It can be seen that the relatively undemanding start from the Main Task was removed in the Target Transfer set. Averaged throughout the whole set, a pattern with a higher average lateral distance to traverse can be found, potentially increasing the difficulty to control the Pendulum for participants, especially when combined with the three occurrences of two sequential targets.

In Tables XI and XII, we can see that the higher hypothesized nominal task difficulty of the Target Transfer is indeed reflected in the Baseline performance being worse for the Target Transfer than for the Main Task, both for Control Group and Experimental Group respectively; the value for the Intercept (representing $ErrorAbs$ at Baseline) is higher for the Target Transfer than the Main Task.

Additionally, in line with our expectations, the Target Transfer exhibits greater stability of difficulty compared to the Main Task, as no significant effect of the specific target within a set ($wIndex$) on performance improvement is observed in the Target Transfer, while this effect is present in the Main Task. In the Main Task, we notice less improvement in later targets (positive estimate of $wIndex$ fixed effect), suggesting a higher difficulty associated with targets later in the set. Furthermore, the second set of the Main Task exhibits a stronger learning effect compared to the first set, (significant effect of $sIndex$), which can be attributed to the fact that the initial set of the Main Task is conducted after a gap of 1-3 days, potentially leading to relatively lower performance as participants need to readjust to the task again.

APPENDIX E
DATA DISTRIBUTIONS

A. *Locus of Control Distribution*

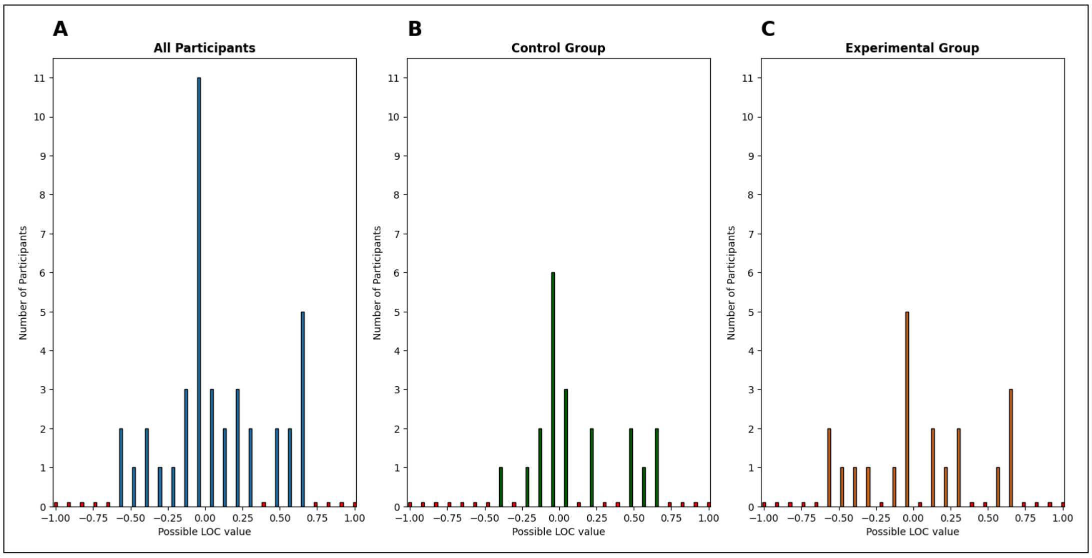

Fig. 8: Distribution of the LOC variable of the 40 participants included in our analyses. Red marks indicate a possible value that no participant possesses. **(A)** All participants included in the experiments, separated in the following two Groups: **(B)** The Control Group. **(C)** The Experimental Group.

The possible values of the LOC variable are:

$$Possible\ LOC\ Values = [1.000, -0.913, -0.826, -0.739, -0.652, -0.565, -0.478, -0.391, -0.304, -0.217, -0.130, -0.043, 0.043, 0.130, 0.217, 0.304, 0.391, 0.478, 0.565, 0.652, 0.739, 0.826, 0.913, 1.000]$$

In Figure 8A, we can see that no participants had LOC scores below -0.565 or above 0.652. Additionally, 11 participants have a score of -0.043. Another value that occurs often is 0.652 (5 participants). After having separated the participants into Groups (8B and C), we can see that the peaks on -0.043 and 0.652 are distributed evenly among the two Groups.

B. *Score and Absolute Error Distribution*

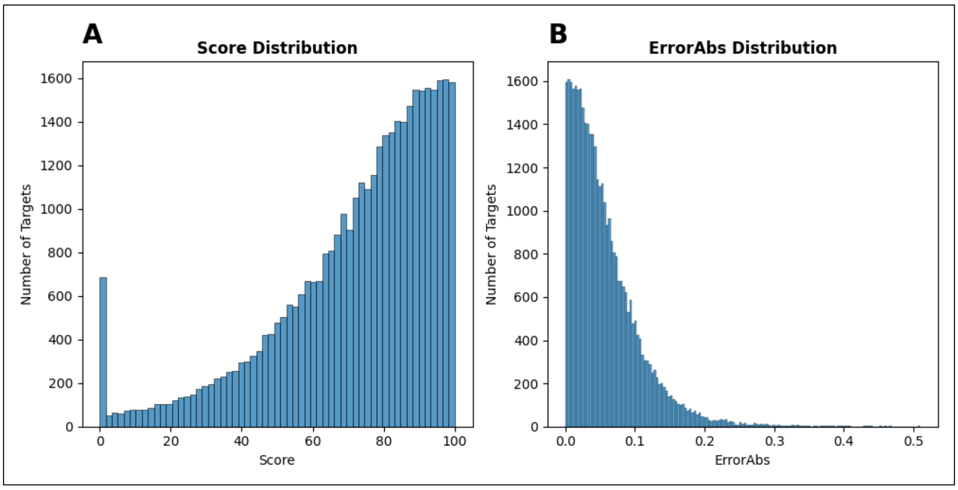

Fig. 9: Distribution of the $Score$ variable (**A**) and the $ErrorAbs$ variable (**B**) for all targets obtained in the experiment. Due to clipping of the Score variable when $ErrorAbs \geq 0.2$ a peak is present at a 0 in the Score distribution.

APPENDIX F
ADDITIONAL OUTCOME METRICS

Some outcome metrics described in prior research [25] [39] can only be calculated for an entire Set as a whole, and not per target individually. Other metrics can be calculated on target level, but when averaged over the entire set provide the opportunity to be compared to this previous research. Additionally, some metrics can provide more insight into our main results. This Appendix contains a description of these metrics.

A. Performance Outcome Metrics

- $SetErrorAbs$: mean Absolute Error of the 20 targets in a Set of a participant. A lower value of this metric denotes better Target hitting Performance.
- $SetScore$: used in [25] and [39], is the mean $Score$ (see Equation 5) of the individual Targets. It is the same outcome metric that the participant gets presented in the Pendulum Game after finishing a Set. A higher value of this metrics denotes better Target hitting Performance.
- $ScoreStd$: is the Standard Deviation of the Score, calculated between the 20 targets in a Set. It can be used as a performance metric, as it tends to decrease with increasing skill level [71] [72] [39] [25].

B. Motion Outcome Metrics

To show how participants behaved during the Pendulum Task. This can provide more insights in why or how good performance in the task is achieved.

- $\omega_N\%PSD$: the Power Spectral Density around the Natural Frequency, calculated per Set. This can be used to investigate whether participants are able to control the Pendulum [25] [39]. The Pendulum has to be moved away from its natural frequency by a participant to properly hit a Target, because the target positions do not follow a pattern that fits the natural periodicity of the pendulum swing [25]. The lower the value of this metric, the less the pendulum is swinging in its natural frequency. This metric has shown to correlate with the $Score$ metric in [25] and [39]. The frequency resolution decreases the fewer targets are selected when calculating this metric, potentially leading to a decrease in correlation with task performance of the metric [39]. Therefore, we decided to calculate it for each Set as a whole.
- $EeStd$: the Standard Deviation of the End-Effector in y-direction during one target, which has shown to significantly differ between Baseline and Retention assessment tests, and between Haptic Guidance and Control Group during training [25]. A higher value describes more fluctuations in the movements of the Robot End-Effector, which may be caused by either the participant, Haptic Guidance, or Haptic Rendering.
- $SetEeStd$: the same outcome metric as described above, but with the Standard Deviation of the time steps of the entire Set, instead of only for one Target.

C. Interaction Outcome Metrics

- $SetIntForceAbs$: the mean of the Absolute Interaction Force measured in all time steps of the entire Set of an individual participant, instead of the $IntForceAbs$, where the mean is taken per Target.

APPENDIX G
MOTOR LEARNING – WITHIN GROUP COMPARISONS

A. Methods

The effect of training on the relative improvement of participants' skill level between Baseline and Retention assessment tests, was evaluated on set level with the regression formula from Equation 17.

$$Metric \sim Group * Stage + sIndex + (1|ID) \tag{17}$$

This model was applied separately to a selection of the outcome metrics that correspond to those used in prior research [39] [25] (see Appendix F) for all three task types; Main Task, Target Transfer and Dynamics Transfer. The resulting models were used to find marginal differences between and within Groups, among retention tests, with the *emmeans* package in R with Tukey's Honest Significant Difference method [55].

B. Within Group Comparisons

For participants in both Groups, changes are found in performance metrics for all Pendulum Tasks when comparing assessment test before and after training. Specifically, the following significant differences are obtained from Baseline to Retention: $SetScore$ increased, $ScoreStd$ decreased. $SetErrorAbs$ decreased.

Additionally, the $EeStd$ increased significantly for all tasks and both Groups from Baseline to Retention. Similar results are found for a decrease in $\omega_N\%PSD$, except for a non-significant decrease in the experimental Group between Baseline and Long-Term Retention in the Main Task. No significant differences are found in either Performance or Motion metrics, between Long-Term Retention and Short-Term Retention assessment tests in all task types.

Comparison		Performance						Motion			
		SetScore (-)		ScoreStd (-)		SetErrorAbs (m)		EeStd (m)		ω_N %PSD (-)	
Stage	**Group**	**Estimate**	**P-Value**	**Estimate**	**P-Value**	**Estimate**	**P-Value**	**Estimate**	**P-Value**	**Estimate**	**P-Value**
STR-BL		12.4738	**<.0001**	-8.780	**<.0001**	-0.0259	**<.0001**	0.01561	**<.0001**	-18.722	**<.0001**
LTR-BL	C	12.3807	**<.0001**	-8.176	**<.0001**	-0.0256	**<.0001**	0.01351	**<.0001**	-9.923	**0.0181**
LTR-STR		-0.0931	1.0000	0.604	0.9789	0.000334	1.0000	-0.00210	0.7672	8.799	0.0522
STR-BL		11.9209	**<.0001**	-7.935	**<.0001**	-0.0251	**<.0001**	0.00665	**0.0005**	-11.292	**0.0041**
LTR-BL	E	12.7623	**<.0001**	-9.083	**<.0001**	-0.0267	**<.0001**	0.00918	**<.0001**	-6.185	0.3393
LTR-STR		0.8414	0.9808	-1.149	0.7420	-0.00160	0.9875	0.00252	0.6001	5.106	0.5592

TABLE VIII: Main Task within Group Comparisons for Performance and Motion metrics

Comparison		Performance						Motion			
		SetScore (-)		ScoreStd (-)		SetErrorAbs (m)		EeStd (m)		ω_N %PSD (-)	
Stage	**Group**	**Estimate**	**P-Value**	**Estimate**	**P-Value**	**Estimate**	**P-Value**	**Estimate**	**P-Value**	**Estimate**	**P-Value**
STR-BL		14.4060	**<.0001**	-6.5843	**<.0001**	-0.029096	**<.0001**	0.012540	**<.0001**	-15.770	**0.0001**
LTR-BL	C	12.1112	**<.0001**	-5.1556	**<.0001**	-0.024296	**<.0001**	0.011635	**<.0001**	-15.312	**0.0001**
LTR-STR		-2.2947	0.1612	1.4287	0.4400	0.004801	0.1350	-0.000905	0.9917	0.457	1.0000
STR-BL		11.7686	**<.0001**	-6.4518	**<.0001**	-0.024180	**<.0001**	0.010830	**<.0001**	-20.055	**<.0001**
LTR-BL	E	11.4131	**<.0001**	-6.6669	**<.0001**	-0.023375	**<.0001**	0.011451	**<.0001**	-18.759	**<.0001**
LTR-STR		-0.3555	0.9991	-0.2151	0.9998	0.000804	0.9984	0.000621	0.9986	1.296	0.9989

TABLE IX: Target Transfer within Group Comparisons for Performance and Motion metrics.

Comparison		Performance						Motion			
		SetScore (-)		ScoreStd (-)		SetErrorAbs (m)		EeStd (m)		ω_N %PSD (-)	
Stage	**Group**	**Estimate**	**P-Value**	**Estimate**	**P-Value**	**Estimate**	**P-Value**	**Estimate**	**P-Value**	**Estimate**	**P-Value**
STR-BL		9.599	**<.0001**	-5.870	**<.0001**	-0.019637	**<.0001**	0.011450	**<.0001**	-17.89	**<.0001**
LTR-BL	C	9.949	**<.0001**	-5.214	**<.0001**	-0.020435	**<.0001**	0.012315	**<.0001**	-15.67	**0.0003**
LTR-STR		0.349	0.9998	0.656	0.9732	-0.000798	0.9997	0.000865	0.9904	2.22	0.9893
STR-BL		4.795	**0.0067**	-3.394	**0.0015**	-0.009929	**0.0063**	0.008631	**<.0001**	-11.26	**0.0223**
LTR-BL	E	6.537	**<.0001**	-4.405	**<.0001**	-0.013450	**<.0001**	0.011028	**<.0001**	-13.41	**0.0030**
LTR-STR		1.743	0.7934	-1.011	0.8474	-0.003521	0.8066	0.002397	0.5442	-2.15	0.9908

TABLE X: Dynamics Transfer within Group Comparisons for Performance and Motion metrics.

APPENDIX H
MOTOR LEARNING – ABSOLUTE ERROR & LOCUS OF CONTROL

Motor Learning Regression Results with $ErrorAbs$ as dependent variable per Task (Equation 7). Not FDR Corrected.

	Main Task ErrorAbs			Target Transfer ErrorAbs			Dynamics Transfer ErrorAbs		
Predictors	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*
(Intercept)	0.06738	0.06042 – 0.07434	**<0.001**	0.07461	0.06791 – 0.08132	**<0.001**	0.06233	0.05517 – 0.06949	**<0.001**
LOC	0.00664	-0.01416 – 0.02743	0.532	0.00278	-0.01735 – 0.02292	0.786	0.01379	-0.00792 – 0.03551	0.213
Stage [STR]	-0.02591	-0.03053 – -0.02129	**<0.001**	-0.03038	-0.03468 – -0.02608	**<0.001**	-0.01817	-0.02236 – -0.01399	**<0.001**
Stage [LTR]	-0.02600	-0.03062 – -0.02138	**<0.001**	-0.02497	-0.02928 – -0.02067	**<0.001**	-0.01846	-0.02265 – -0.01428	**<0.001**
Group [E]	0.00051	-0.00845 – 0.00948	0.910	0.00094	-0.00774 – 0.00962	0.832	-0.00453	-0.01389 – 0.00483	0.343
wIndex	0.00078	0.00056 – 0.00099	**<0.001**	0.00017	-0.00003 – 0.00037	0.095	0.00061	0.00042 – 0.00081	**<0.001**
sIndex	-0.00172	-0.00421 – 0.00077	0.175	-0.00187	-0.00419 – 0.00045	0.114	-0.00667	-0.00893 – -0.00442	**<0.001**
LOC × Stage [STR]	0.00020	-0.01450 – 0.01491	0.978	0.01135	-0.00235 – 0.02505	0.104	-0.01294	-0.02626 – 0.00038	0.057
LOC × Stage [LTR]	0.00393	-0.01078 – 0.01863	0.601	0.00599	-0.00771 – 0.01969	0.392	-0.01747	-0.03079 – -0.00414	**0.010**
LOC × Group [E]	-0.01056	-0.03670 – 0.01559	0.429	-0.00544	-0.03076 – 0.01988	0.674	-0.01031	-0.03762 – 0.01700	0.459
Stage [STR] × Group [E]	0.00047	-0.00587 – 0.00681	0.885	0.00584	-0.00007 – 0.01175	0.053	0.00823	0.00248 – 0.01397	**0.005**
Stage [LTR] × Group [E]	-0.00127	-0.00762 – 0.00507	0.694	0.00106	-0.00484 – 0.00697	0.724	0.00453	-0.00121 – 0.01028	0.122
(LOC × Stage [STR]) × Group [E]	0.00673	-0.01176 – 0.02523	0.475	-0.00386	-0.02109 – 0.01337	0.661	0.01334	-0.00341 – 0.03010	0.118
(LOC × Stage [LTR]) × Group [E]	0.00779	-0.01070 – 0.02628	0.409	0.00515	-0.01207 – 0.02238	0.558	0.02741	0.01066 – 0.04416	**0.001**
Random Effects									
σ^2	0.00193			0.00168			0.00159		
τ_{00}	0.00014_{ID}			0.00014_{ID}			0.00017_{ID}		
ICC	0.06971			0.07666			0.09736		
N	40_{ID}			40_{ID}			40_{ID}		
Observations	4800			4800			4800		
Marginal R^2 / Conditional R^2	0.077 / 0.142			0.078 / 0.149			0.050 / 0.143		
AIC	-16121.358			-16797.590			-17056.182		

TABLE XI: Control Group as reference.

	Main Task ErrorAbs			Target Transfer ErrorAbs			Dynamics Transfer ErrorAbs		
Predictors	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*
(Intercept)	0.06789	0.06130 – 0.07449	**<0.001**	0.07555	0.06920 – 0.08191	**<0.001**	0.05780	0.05103 – 0.06457	**<0.001**
LOC	-0.00392	-0.01977 – 0.01193	0.628	-0.00266	-0.01801 – 0.01269	0.734	0.00348	-0.01307 – 0.02004	0.680
Stage [STR]	-0.02544	-0.02979 – -0.02110	**<0.001**	-0.02454	-0.02858 – -0.02049	**<0.001**	-0.00995	-0.01388 – -0.00601	**<0.001**
Stage [LTR]	-0.02727	-0.03161 – -0.02293	**<0.001**	-0.02391	-0.02795 – -0.01986	**<0.001**	-0.01393	-0.01786 – -0.00999	**<0.001**
Group [C]	-0.00051	-0.00948 – 0.00845	0.910	-0.00094	-0.00962 – 0.00774	0.832	0.00453	-0.00483 – 0.01389	0.343
wIndex	0.00078	0.00056 – 0.00099	**<0.001**	0.00017	-0.00003 – 0.00037	0.095	0.00061	0.00042 – 0.00081	**<0.001**
sIndex	-0.00172	-0.00421 – 0.00077	0.175	-0.00187	-0.00419 – 0.00045	0.114	-0.00667	-0.00893 – -0.00442	**<0.001**
LOC × Stage [STR]	0.00694	-0.00427 – 0.01815	0.225	0.00749	-0.00296 – 0.01793	0.160	0.00040	-0.00975 – 0.01056	0.938
LOC × Stage [LTR]	0.01172	0.00050 – 0.02293	**0.041**	0.01114	0.00070 – 0.02158	**0.037**	0.00994	-0.00021 – 0.02010	0.055
LOC × Group [C]	0.01056	-0.01559 – 0.03670	0.429	0.00544	-0.01988 – 0.03076	0.674	0.01031	-0.01700 – 0.03762	0.459
Stage [STR] × Group [C]	-0.00047	-0.00681 – 0.00587	0.885	-0.00584	-0.01175 – 0.00007	0.053	-0.00823	-0.01397 – -0.00248	**0.005**
Stage [LTR] × Group [C]	0.00127	-0.00507 – 0.00762	0.694	-0.00106	-0.00697 – 0.00484	0.724	-0.00453	-0.01028 – 0.00121	0.122
(LOC × Stage [STR]) × Group [C]	-0.00673	-0.02523 – 0.01176	0.475	0.00386	-0.01337 – 0.02109	0.661	-0.01334	-0.03010 – 0.00341	0.118
(LOC × Stage [LTR]) × Group [C]	-0.00779	-0.02628 – 0.01070	0.409	-0.00515	-0.02238 – 0.01207	0.558	-0.02741	-0.04416 – -0.01066	**0.001**
Random Effects									
σ^2	0.00193			0.00168			0.00159		
τ_{00}	0.00014_{ID}			0.00014_{ID}			0.00017_{ID}		
ICC	0.06971			0.07666			0.09736		
N	40_{ID}			40_{ID}			40_{ID}		
Observations	4800			4800			4800		
Marginal R^2 / Conditional R^2	0.077 / 0.142			0.078 / 0.149			0.050 / 0.143		
AIC	-16121.358			-16797.590			-17056.182		

TABLE XII: Experimental Group as reference.

Motor Learning Regression Results with $ErrorAbs$ as dependent variable per Task (Equation 7). FDR Corrected.

	Main Task ErrorAbs			Target Transfer ErrorAbs			Dynamics Transfer ErrorAbs		
Predictors	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*
(Intercept)	0.06738	0.06042 – 0.07434	**<0.001**	0.07461	0.06791 – 0.08132	**<0.001**	0.06233	0.05517 – 0.06949	**<0.001**
LOC	0.00664	-0.01416 – 0.02743	0.827	0.00278	-0.01735 – 0.02292	0.832	0.01379	-0.00792 – 0.03551	0.249
Stage [STR]	-0.02591	-0.03053 – -0.02129	**<0.001**	-0.03038	-0.03468 – -0.02608	**<0.001**	-0.01817	-0.02236 – -0.01399	**<0.001**
Stage [LTR]	-0.02600	-0.03062 – -0.02138	**<0.001**	-0.02497	-0.02928 – -0.02067	**<0.001**	-0.01846	-0.02265 – -0.01428	**<0.001**
Group [E]	0.00051	-0.00845 – 0.00948	0.978	0.00094	-0.00774 – 0.00962	0.832	-0.00453	-0.01389 – 0.00483	0.369
wIndex	0.00078	0.00056 – 0.00099	**<0.001**	0.00017	-0.00003 – 0.00037	0.227	0.00061	0.00042 – 0.00081	**<0.001**
sIndex	-0.00172	-0.00421 – 0.00077	0.489	-0.00187	-0.00419 – 0.00045	0.227	-0.00667	-0.00893 – -0.00442	**<0.001**
LOC × Stage [STR]	0.00020	-0.01450 – 0.01491	0.978	0.01135	-0.00235 – 0.02505	0.227	-0.01294	-0.02626 – 0.00038	0.089
LOC × Stage [LTR]	0.00393	-0.01078 – 0.01863	0.841	0.00599	-0.00771 – 0.01969	0.685	-0.01747	-0.03079 – -0.00414	**0.018**
LOC × Group [E]	-0.01056	-0.03670 – 0.01559	0.827	-0.00544	-0.03076 – 0.01988	0.832	-0.01031	-0.03762 – 0.01700	0.459
Stage [STR] × Group [E]	0.00047	-0.00587 – 0.00681	0.978	0.00584	-0.00007 – 0.01175	0.184	0.00823	0.00248 – 0.01397	**0.010**
Stage [LTR] × Group [E]	-0.00127	-0.00762 – 0.00507	0.883	0.00106	-0.00484 – 0.00697	0.832	0.00453	-0.00121 – 0.01028	0.155
(LOC × Stage [STR]) × Group [E]	0.00673	-0.01176 – 0.02523	0.827	-0.00386	-0.02109 – 0.01337	0.832	0.01334	-0.00341 – 0.03010	0.155
(LOC × Stage [LTR]) × Group [E]	0.00779	-0.01070 – 0.02628	0.827	0.00515	-0.01207 – 0.02238	0.832	0.02741	0.01066 – 0.04416	**0.003**
Random Effects									
σ^2	0.00193			0.00168			0.00159		
τ_{00}	0.00014_{ID}			0.00014_{ID}			0.00017_{ID}		
ICC	0.06971			0.07666			0.09736		
N	40_{ID}			40_{ID}			40_{ID}		
Observations	4800			4800			4800		
Marginal R^2 / Conditional R^2	0.077 / 0.142			0.078 / 0.149			0.050 / 0.143		
AIC	-16121.358			-16797.590			-17056.182		

TABLE XIII: Control Group as reference.

	Main Task ErrorAbs			Target Transfer ErrorAbs			Dynamics Transfer ErrorAbs		
Predictors	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*
(Intercept)	0.06789	0.06130 – 0.07449	**<0.001**	0.07555	0.06920 – 0.08191	**<0.001**	0.05780	0.05103 – 0.06457	**<0.001**
LOC	-0.00392	-0.01977 – 0.01193	0.799	-0.00266	-0.01801 – 0.01269	0.791	0.00348	-0.01307 – 0.02004	0.732
Stage [STR]	-0.02544	-0.02979 – -0.02110	**<0.001**	-0.02454	-0.02858 – -0.02049	**<0.001**	-0.00995	-0.01388 – -0.00601	**<0.001**
Stage [LTR]	-0.02727	-0.03161 – -0.02293	**<0.001**	-0.02391	-0.02795 – -0.01986	**<0.001**	-0.01393	-0.01786 – -0.00999	**<0.001**
Group [C]	-0.00051	-0.00948 – 0.00845	0.910	-0.00094	-0.00962 – 0.00774	0.832	0.00453	-0.00483 – 0.01389	0.436
wIndex	0.00078	0.00056 – 0.00099	**<0.001**	0.00017	-0.00003 – 0.00037	0.222	0.00061	0.00042 – 0.00081	**<0.001**
sIndex	-0.00172	-0.00421 – 0.00077	0.407	-0.00187	-0.00419 – 0.00045	0.227	-0.00667	-0.00893 – -0.00442	**<0.001**
LOC × Stage [STR]	0.00694	-0.00427 – 0.01815	0.450	0.00749	-0.00296 – 0.01793	0.280	0.00040	-0.00975 – 0.01056	0.938
LOC × Stage [LTR]	0.01172	0.00050 – 0.02293	0.114	0.01114	0.00070 – 0.02158	0.128	0.00994	-0.00021 – 0.02010	0.096
LOC × Group [C]	0.01056	-0.01559 – 0.03670	0.665	0.00544	-0.01988 – 0.03076	0.791	0.01031	-0.01700 – 0.03762	0.536
Stage [STR] × Group [C]	-0.00047	-0.00681 – 0.00587	0.910	-0.00584	-0.01175 – 0.00007	0.147	-0.00823	-0.01397 – -0.00248	**0.010**
Stage [LTR] × Group [C]	0.00127	-0.00507 – 0.00762	0.809	-0.00106	-0.00697 – 0.00484	0.791	-0.00453	-0.01028 – 0.00121	0.170
(LOC × Stage [STR]) × Group [C]	-0.00673	-0.02523 – 0.01176	0.665	0.00386	-0.01337 – 0.02109	0.791	-0.01334	-0.03010 – 0.00341	0.170
(LOC × Stage [LTR]) × Group [C]	-0.00779	-0.02628 – 0.01070	0.665	-0.00515	-0.02238 – 0.01207	0.791	-0.02741	-0.04416 – -0.01066	**0.003**
Random Effects									
σ^2	0.00193			0.00168			0.00159		
τ_{00}	0.00014_{ID}			0.00014_{ID}			0.00017_{ID}		
ICC	0.06971			0.07666			0.09736		
N	40_{ID}			40_{ID}			40_{ID}		
Observations	4800			4800			4800		
Marginal R^2 / Conditional R^2	0.077 / 0.142			0.078 / 0.149			0.050 / 0.143		
AIC	-16121.358			-16797.590			-17056.182		

TABLE XIV: Experimental Group as reference.

Motor Learning Regression Results with $ErrorAbs$ as dependent variable per Task (Equation 7, without $Group$ variable). Not FDR Corrected.

	Main Task ErrorAbs (no Group)			Target Transfer ErrorAbs (no Group)			Dynamics Transfer ErrorAbs (no Group)		
Predictors	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*
(Intercept)	0.06792	0.06296 – 0.07287	**<0.001**	0.07524	0.07046 – 0.08001	**<0.001**	0.06028	0.05527 – 0.06530	**<0.001**
LOC	0.00002	-0.01228 – 0.01232	0.998	-0.00072	-0.01269 – 0.01125	0.906	0.00803	-0.00479 – 0.02084	0.220
Stage [LTR]	-0.02685	-0.02998 – -0.02372	**<0.001**	-0.02456	-0.02748 – -0.02165	**<0.001**	-0.01685	-0.01970 – -0.01401	**<0.001**
Stage [STR]	-0.02585	-0.02898 – -0.02272	**<0.001**	-0.02729	-0.03021 – -0.02438	**<0.001**	-0.01432	-0.01716 – -0.01148	**<0.001**
wIndex	0.00078	0.00056 – 0.00099	**<0.001**	0.00017	-0.00003 – 0.00037	0.095	0.00061	0.00042 – 0.00081	**<0.001**
sIndex	-0.00172	-0.00421 – 0.00076	0.174	-0.00187	-0.00419 – 0.00045	0.114	-0.00667	-0.00893 – -0.00442	**<0.001**
LOC × Stage [LTR]	0.00893	0.00006 – 0.01781	**0.048**	0.00904	0.00077 – 0.01730	**0.032**	-0.00110	-0.00915 – 0.00696	0.790
LOC × Stage [STR]	0.00432	-0.00456 – 0.01319	0.340	0.00815	-0.00012 – 0.01641	0.053	-0.00580	-0.01386 – 0.00225	0.158
Random Effects									
σ^2	0.00193			0.00168			0.00159		
τ_{00}	0.00014_{ID}			0.00013_{ID}			0.00016_{ID}		
ICC	0.06637			0.07394			0.09216		
N	40_{ID}			40_{ID}			40_{ID}		
Observations	4800			4800			4800		
Marginal R^2 / Conditional R^2	0.077 / 0.138			0.076 / 0.145			0.046 / 0.134		
AIC	-16183.210			-16855.853			-17097.626		

TABLE XV: Control Group and Experimental Group combined.

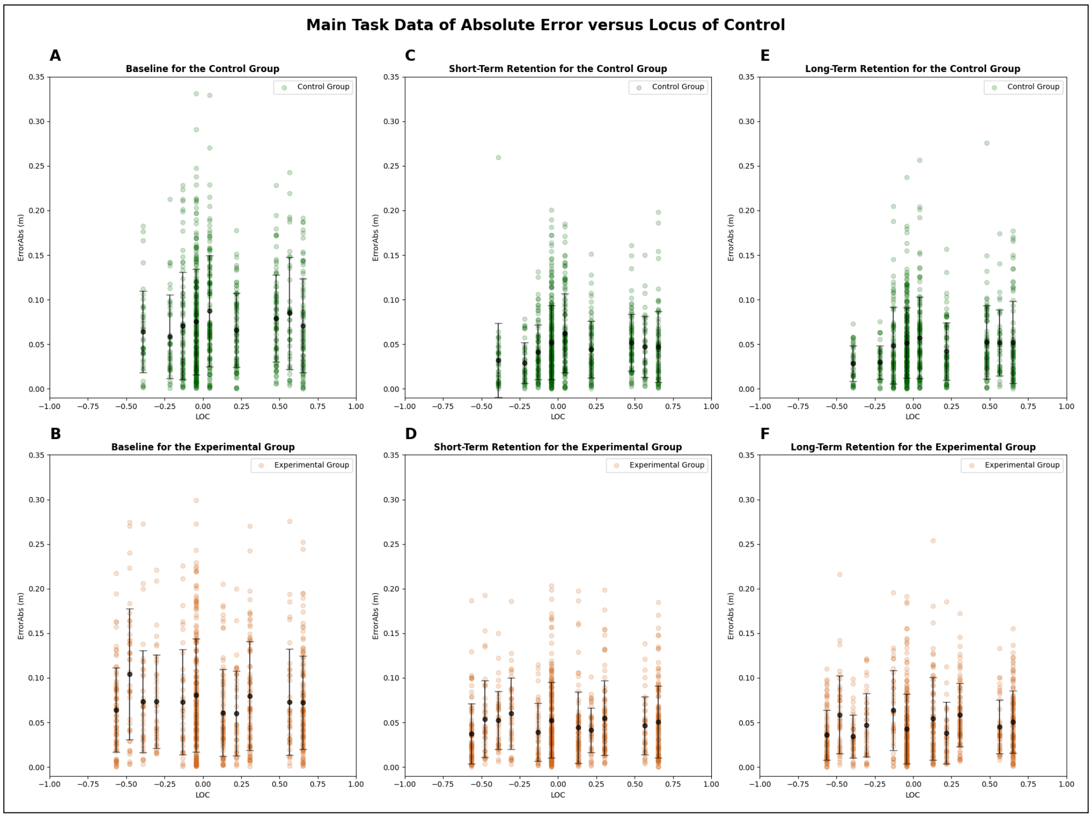

Fig. 10: Main Task Absolute Error for each Stage per Group: **(A-B)** Baseline, (**C-D**) Short-Term Retention and (**E-F**) Long-Term Retention. For each Locus of Control value, the Mean and Standard Deviation are shown over in black for all targets and all participants with the respective Locus of Control value, according to the distribution in Figure 8, B and C (Appendix E).

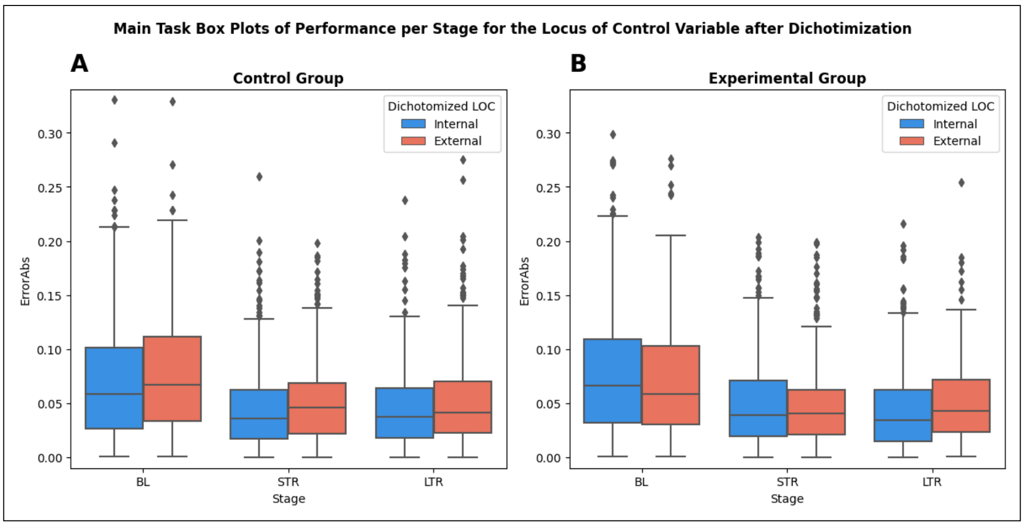

Fig. 11: Main Task Box Plots for each Stage per Group after Dichotomization of the LOC variable: **(A)** Control Group, (**B**) Experimental Group. LOC values below zero are included in Internal LOC and above zero in External LOC.

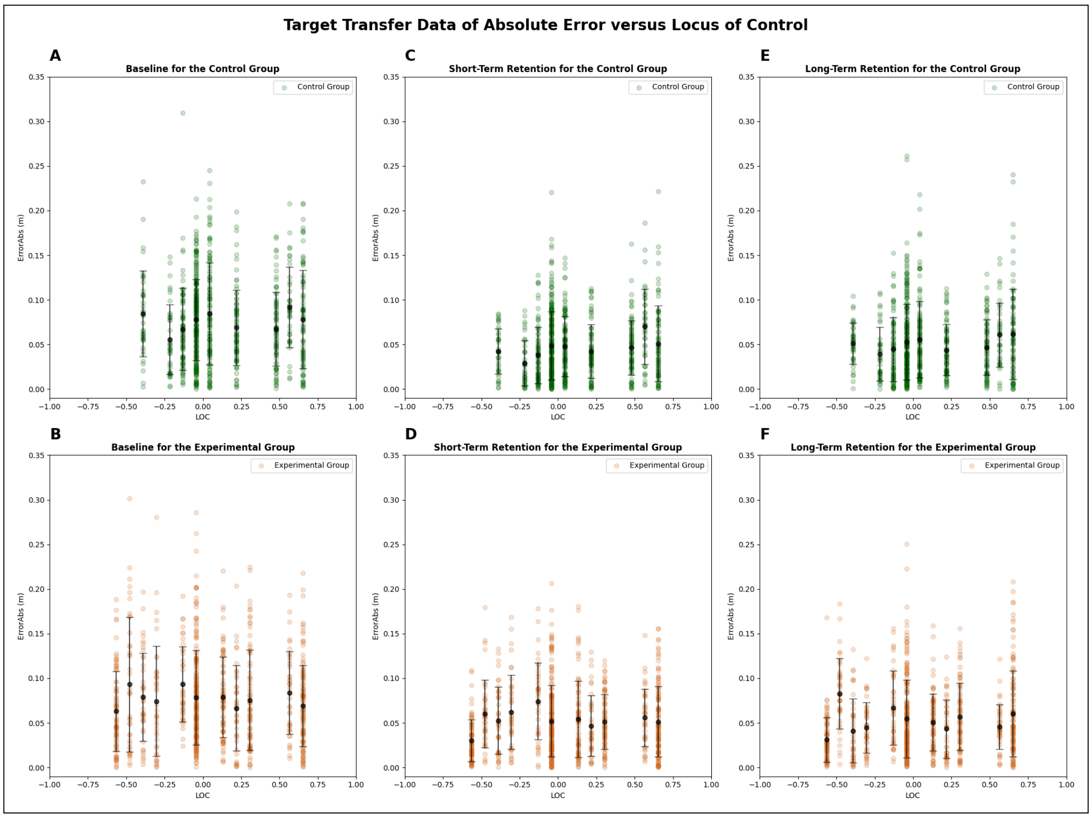

Fig. 12: Target Transfer Absolute Error for each Stage per Group: **(A-B)** Baseline, (**C-D**) Short-Term Retention and (**E-F**) Long-Term Retention. For each Locus of Control value, the Mean and Standard Deviation are shown over in black for all targets and all participants with the respective Locus of Control value, according to the distribution in Figure 8, B and C (Appendix E).

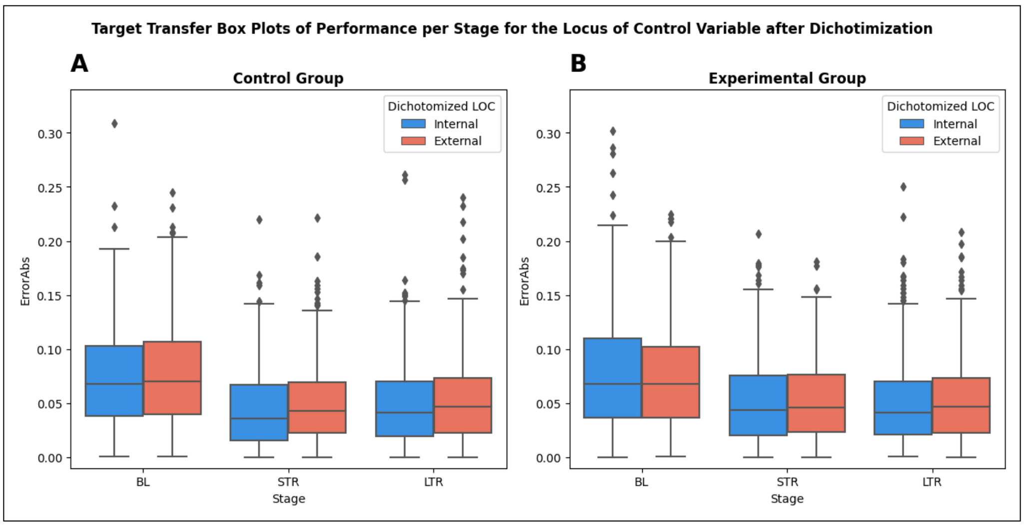

Fig. 13: Target Transfer Performance Box Plots for each Stage per Group after Dichotomization of the LOC variable: **(A)** Control Group, (**B**) Experimental Group. LOC values below zero are included in Internal LOC and above zero in External LOC.

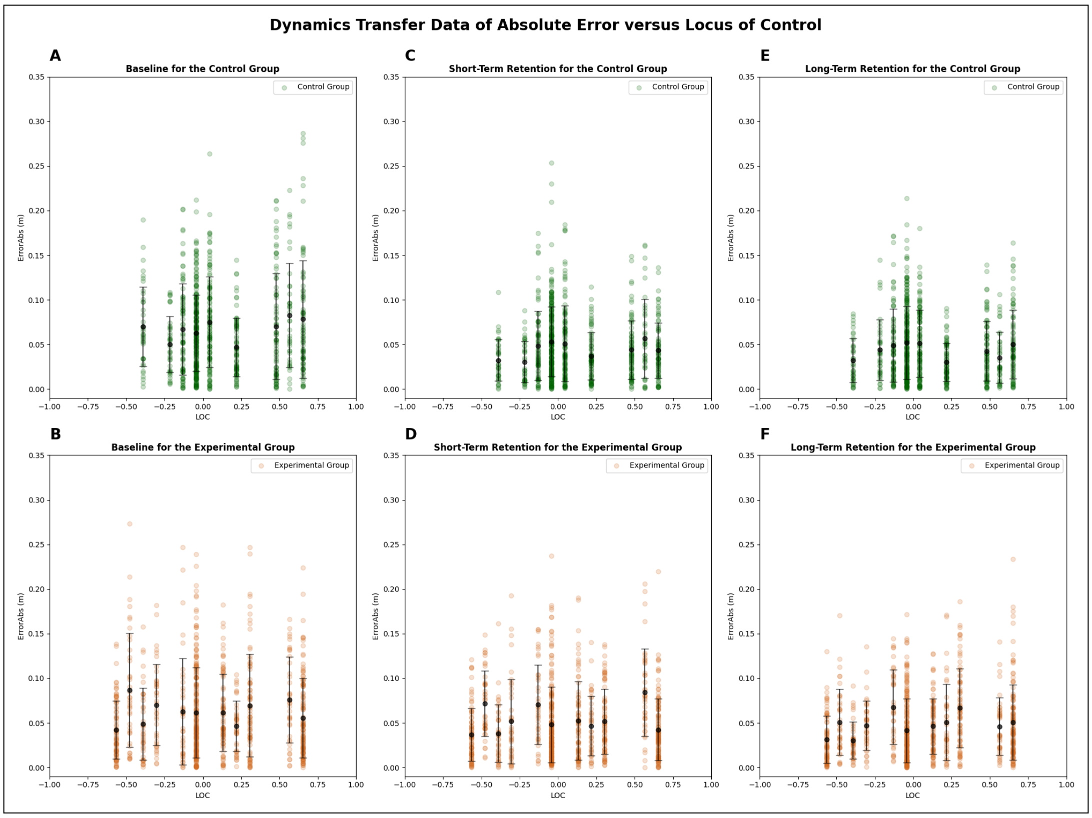

Fig. 14: Dynamics Transfer Absolute Error for each Stage per Group: **(A-B)** Baseline, (**C-D**) Short-Term Retention and (**E-F**) Long-Term Retention. For each Locus of Control value, the Mean and Standard Deviation are shown over in black for all targets and all participants with the respective Locus of Control value, according to the distribution in Figure 8, B and C (Appendix E).

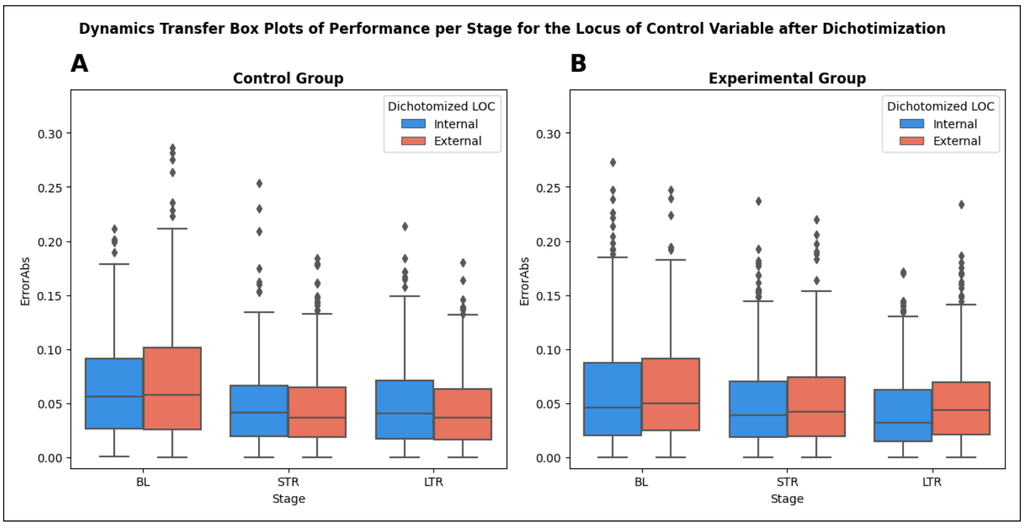

Fig. 15: Dynamics Transfer Performance Box Plots for each Stage per Group after Dichotomization of the LOC variable: (**A**) Control Group, (**B**) Experimental Group. LOC values below zero are included in Internal LOC and above zero in External LOC.

Appendix I
Motor Learning – Absolute Error Difference per Target & Locus of Control

A. Methods

Prior research has shown that Motor Learning effects of Haptic training strategies depend on a person's initial skill level [3]. Even though Equation 7 does take initial skill level into account through the Baseline value of the Stage variable, the variable cannot be used as a predictor for relative improvement in a new participant based on their specific initial skill level. Therefore, we used the formula in Equation 18, which includes the Absolute Error at Baseline for each Task as a separate predictor ($ErrorAbs_{Bl}$), to model the difference in Absolute Error between targets from Long-Term Retention and Baseline ($dErrorAbs_{LtrBl}$). We included only Long-Term Retention, as results from Motor Learning analyses based on Equation 7 did not show promising results in Short-Term Retention.

$$dErrorAbs_{LtrBl} \sim ErrorAbs_{Bl} + LOC * Group + sIndex + wIndex + (1|ID) \tag{18}$$

$ErrorAbs_{Bl}$ is used to model initial skill level of a participant at Baseline per Task. The variable is centered around the mean; a positive value denotes a higher Absolute Error for a specific target than the average in all participants for that Task.

B. Results

With Equation 18, we evaluated whether the Locus of Control affects the relative improvement per target in individuals, by assessing the fixed effect of LOC, and whether this effect is different between training methods through its interaction effect with $Group$. This type of modeling did not provide significant results with respect to the Locus of Control variable (see Tables XVI and XVII).

Our results do show a high usability of one's initial skill level to predict performance improvement, represented by significant effects of the $ErrorAbs_{Bl}$ variable, with p-values under 0.001 for all tasks in both Groups. Since this variable is centered around the mean of Baseline performance for all participants in the corresponding task, the Intercept represents the average reduction in Absolute Error between Baseline and Long-Term Retention for an individual with a Locus of Control score of 0.

C. Discussion

This method depends severely on the highly variable baseline performance, which, combined with the lower amount of data (only $1/3$rd of the total available data), does not provide useful results. This is reflected in the high confidence intervals as well. Therefore, our approach from 7 seems the best suited for our motor learning analysis.

Note that for both Equations 7 and 18, additional modifications regarding the random effect per participant, $(1|ID)$, such as use of the $Stage$, $wIndex$ or $sIndex$ variable as random slope, resulted in either non-convergence or lower Goodness of Fit, described by the Akaike Information Criterion (AIC) [73]. Therefore, we did not include any of these variables in the random effect.

Removal of the fixed effects of the $wIndex$ and $sIndex$ variables, lead to a lower AIC in the resulting models for some Tasks, but they are still included in our analysis. This way, it is possible to compare their effects between Tasks through evaluation of potential performance differences within Sets ($wIndex$) and between Sets ($sIndex$) for each Task.

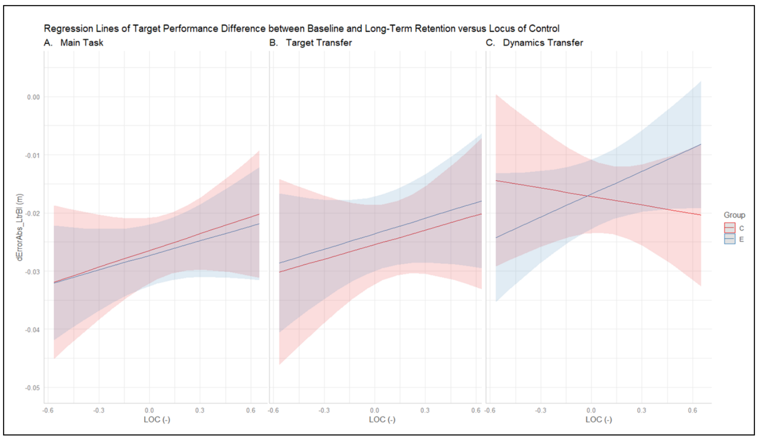

Fig. 16: Long Term Performance Increase per Group depending on Locus of Control tendency, denoted by the difference in Absolute Error per target compared between targets from Long-Term Retention and Baseline, **(A)** for the Control Group and **(B)** for the Experimental Group, based on Equation 18.

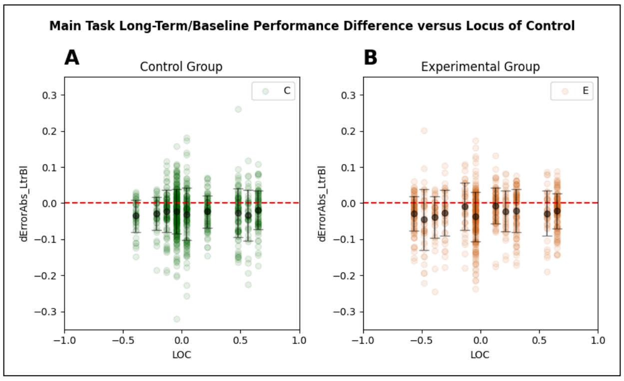

Fig. 17: Main Task Performance Difference in Absolute Error compared between targets from Long-Term Retention and Baseline depending on Locus of Control. Visualized per Group: **(A)** for the Control Group and **(B)** for the Experimental Group. Mean and standard deviation are shown per Locus of Control value, showing that on average people decreased their Absolute Error, and thus improved their performance, as all mean difference values are below the red dashed line of zero difference.

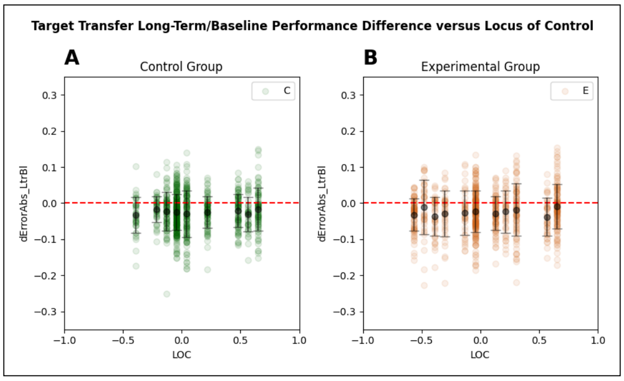

Fig. 18: Target Transfer Performance Difference in Absolute Error compared between targets from Long-Term Retention and Baseline depending on Locus of Control. Visualized per Group: **(A)** for the Control Group and **(B)** for the Experimental Group. Mean and standard deviation are shown per Locus of Control value, showing that on average people decreased their Absolute Error, and thus improved their performance, as all mean difference values are below the red dashed line of zero difference.

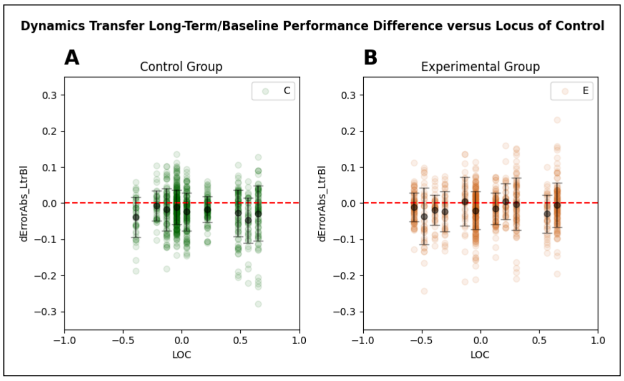

Fig. 19: Dynamics Transfer Performance Difference in Absolute Error compared between targets from Long-Term Retention and Baseline depending on Locus of Control. Visualized per Group: **(A)** for the Control Group and **(B)** for the Experimental Group. Mean and standard deviation are shown per Locus of Control value, showing that on average people decreased their Absolute Error, and thus improved their performance, as all mean difference values are below the red dashed line of zero difference.

Regression Results of Individual ErrorAbs Target Difference between Baseline and Long-Term Retention (Equation 18). Not FDR Corrected.

	Main Task dErrorAbs_LtrBl			Target Transfer dErrorAbs_LtrBl			Dynamics Transfer dErrorAbs_LtrBl		
Predictors	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*
(Intercept)	-0.02866	-0.03521 – -0.02211	**<0.001**	-0.02435	-0.03196 – -0.01674	**<0.001**	-0.01760	-0.02469 – -0.01052	**<0.001**
ErrorAbs Bl Centered	-0.85436	-0.88657 – -0.82216	**<0.001**	-0.84227	-0.87880 – -0.80575	**<0.001**	-0.91254	-0.94920 – -0.87588	**<0.001**
LOC	0.00960	-0.00821 – 0.02740	0.291	0.00833	-0.01330 – 0.02996	0.450	-0.00488	-0.02488 – 0.01512	0.632
Group [E]	-0.00084	-0.00851 – 0.00684	0.831	0.00186	-0.00747 – 0.01118	0.696	0.00040	-0.00822 – 0.00902	0.927
wIndex	0.00064	0.00033 – 0.00095	**<0.001**	0.00001	-0.00030 – 0.00032	0.952	0.00012	-0.00017 – 0.00042	0.414
sIndex	-0.00778	-0.01131 – -0.00425	**<0.001**	-0.00237	-0.00593 – 0.00119	0.192	-0.00151	-0.00493 – 0.00191	0.387
LOC × Group [E]	-0.00123	-0.02362 – 0.02116	0.914	0.00057	-0.02663 – 0.02777	0.967	0.01800	-0.00714 – 0.04315	0.160
Random Effects									
σ^2	0.00130			0.00132			0.00120		
τ_{00}	0.00011 $_{ID}$			0.00018 $_{ID}$			0.00015 $_{ID}$		
ICC	0.07766			0.11786			0.11021		
N	40 $_{ID}$			40 $_{ID}$			40 $_{ID}$		
Observations	1600			1600			1600		
Marginal R^2 / Conditional R^2	0.628 / 0.656			0.543 / 0.597			0.601 / 0.645		
AIC	-5958.737			-5919.585			-6071.076		

TABLE XVI: Control Group as reference.

	Main Task dErrorAbs_LtrBl			Target Transfer dErrorAbs_LtrBl			Dynamics Transfer dErrorAbs_LtrBl		
Predictors	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*
(Intercept)	-0.02950	-0.03576 – -0.02323	**<0.001**	-0.02250	-0.02975 – -0.01525	**<0.001**	-0.01720	-0.02396 – -0.01044	**<0.001**
ErrorAbs Bl Centered	-0.85436	-0.88657 – -0.82216	**<0.001**	-0.84227	-0.87880 – -0.80575	**<0.001**	-0.91254	-0.94920 – -0.87588	**<0.001**
LOC	0.00837	-0.00520 – 0.02194	0.227	0.00890	-0.00759 – 0.02539	0.290	0.01312	-0.00212 – 0.02837	0.092
Group [C]	0.00084	-0.00684 – 0.00851	0.831	-0.00186	-0.01118 – 0.00747	0.696	-0.00040	-0.00902 – 0.00822	0.927
wIndex	0.00064	0.00033 – 0.00095	**<0.001**	0.00001	-0.00030 – 0.00032	0.952	0.00012	-0.00017 – 0.00042	0.414
sIndex	-0.00778	-0.01131 – -0.00425	**<0.001**	-0.00237	-0.00593 – 0.00119	0.192	-0.00151	-0.00493 – 0.00191	0.387
LOC × Group [C]	0.00123	-0.02116 – 0.02362	0.914	-0.00057	-0.02777 – 0.02663	0.967	-0.01800	-0.04315 – 0.00714	0.160
Random Effects									
σ^2	0.00130			0.00132			0.00120		
τ_{00}	0.00011 $_{ID}$			0.00018 $_{ID}$			0.00015 $_{ID}$		
ICC	0.07766			0.11786			0.11021		
N	40 $_{ID}$			40 $_{ID}$			40 $_{ID}$		
Observations	1600			1600			1600		
Marginal R^2 / Conditional R^2	0.628 / 0.656			0.543 / 0.597			0.601 / 0.645		
AIC	-5958.737			-5919.585			-6071.076		

TABLE XVII: Experimental Group as reference.

APPENDIX J
TRAINING – WITHIN & BETWEEN GROUP COMPARISONS

A. Methods

We adapted the Haptic Guidance strategy from Ozen et al. [25], and we intended this strategy to aid participants in performance and in motion metrics when collaborating with it. To validate this, we compare differences in Performance and Motrion outcome metrics (see Appendix F). These differences are between Catch and non-Catch Sets (Catch - nCatch), and between participants from different Groups (E - C). In the Experimental (non-Catch) the Control Group does not receive Haptic Guidance, while the Experimental Group does receive Haptic Guidance (see Figure 3). Comparison are performed using the $emmeans$ package in R, with Tukey's Honest Significant Difference method [55].

The following variable is new in this analysis:

- $SetType$: variable denoting whether data is from a Catch Set (Catch) or Experimental, non-Catch, Set (nCatch), in line with Figure 3.

The following regression formula was used:

$$Metric \sim Group * SetType * trIndex + (1|ID). \tag{19}$$

Table XVIII shows the results of the comparisons, for a selection of outcome metrics. This Table shows that Performance for the Experimental Group's is significantly different between Catch sets (when Haptic Guidance is present) and non-Catch sets (higher $SetScore$, lower $ScoreStd$, lower $SetErrorAbs$ in non-Catch than Catch sets). For the Control Group, who did not receive Haptic Guidance in Catch nor non-Catch sets, Performance does not significantly differ between the two as expected. When comparing the two Groups in Performance, no significant difference is found between Catch nor non-Catch sets.

B. Results

Table XVIII shows significantly better Performance during training with compared to without Haptic Guidance within our Experimental Group, denoted by significantly higher $Score$, lower $ScoreStd$ and lower $ErrorAbs$ for the Experimental Group during training in non-Catch sets (Haptic Guidance present) versus Catch sets (Haptic Guidance OFF).

Comparison		Performance						Motion				Interaction	
		SetScore (-)		ScoreStd (-)		SetErrorAbs (m)		SetEeStd (m)		ω_N %PSD (-)		SetIntForceAbs (N)	
Set Type	**Group**	**Est.**	**p-Value**	**Est.**	**p-Value**	**Est.**	**p-Value**	**Est.**	**p-Value**	**Est.**	**p-Value**	**Est.**	**p-Value**
Catch - nCatch	C	0.907	0.7361	-0.866	0.3970	-0.00194	0.7970	0.000168	0.9969	-7.02	**0.0004**	-0.0442	0.6892
Catch - nCatch	E	-7.829	**<.0001**	4.081	**<.0001**	0.01472	**<.0001**	-0.003845	**<.0001**	8.00	**<.0001**	-2.6523	**<.0001**
Catch	E - C	-4.943	0.2992	2.908	0.1753	0.01120	0.3547	-0.001182	0.9439	1.80	0.9532	0.1125	0.8060
nCatch	E - C	3.793	0.4719	-2.039	0.3782	-0.00546	0.8218	0.002831	0.4527	-13.22	**0.0002**	2.7205	**<.0001**
Catch - nCatch	E - C	-8.74	**<.0001**	4.95	**<.0001**	0.0167	**<.0001**	-0.00401	**0.0005**	15	**<.0001**	-2.61	**<.0001**

TABLE XVIII: Training within and between Group interactions for catch and non-catch (nCatch) sets, with metrics calculated on set level.

C. Discussion

It is likely that the relatively lower performance when Haptic Guidance is not present in the Experimental Group, is due to After Effects from the collaboration with Haptic Guidance, which commonly occurs when people get used to the support provided by Human Robot Interaction [74]. Especially, since no statistical significant difference was obtained in non-Catch sets when comparing Performance between Groups (nCatch, E-C). This shows that our Haptic Guidance strategy does not yield overall superior results during training, and with this a potential increase in Intrinsic Motivation, which is thought to be associated with relatively higher training performance [21] [22], is not assumed to be present.

However, our Haptic Guidance strategy does seem to enforce a strategy that results in a relatively lower percentage of Power Spectral Density around the Natural Frequency ($\omega_N \%PSD$), which is positively associated with motor performance [25] [39]. This becomes evident when comparing non-Catch sets between the Experimental and Control Groups, which shows a significantly higher $\omega_N \%PSD$ in the Control Group than the Experimental Group (difference of -13.22 $p = 0.0002$), without causing a more variable End-Effector movement (non-significant difference in End-Effector Std between C and E for non-Catch sets), which could potentially be present if the Haptic Guidance strategy resulted in highly unstable behavior.

APPENDIX K
TRAINING – HAPTIC GUIDANCE & LOCUS OF CONTROL

Regression Results of Absolute Error and Interaction Force During Training in Non-Catch Sets (Equation 8). Not FDR Corrected.

	Training ErrorAbs			Training IntForceAbs		
Predictors	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*
(Intercept)	0.06115	0.05129 – 0.07101	**<0.001**	0.37110	0.17381 – 0.56839	**<0.001**
trIndex	-0.00074	-0.00086 – -0.00062	**<0.001**	-0.00373	-0.00582 – -0.00163	**0.001**
LOC	0.00929	-0.02189 – 0.04048	0.559	-0.05552	-0.68044 – 0.56941	0.862
Group [E]	-0.00137	-0.01482 – 0.01207	0.841	2.88070	2.61125 – 3.15015	**<0.001**
wIndex	0.00071	0.00060 – 0.00083	**<0.001**	0.03146	0.02939 – 0.03353	**<0.001**
trIndex × LOC	0.00008	-0.00029 – 0.00046	0.666	0.00396	-0.00272 – 0.01064	0.246
trIndex × Group [E]	-0.00019	-0.00035 – -0.00003	**0.023**	-0.01235	-0.01523 – -0.00947	**<0.001**
LOC × Group [E]	-0.01560	-0.05482 – 0.02362	0.436	0.54193	-0.24388 – 1.32774	0.176
(trIndex × LOC) × Group [E]	0.00026	-0.00022 – 0.00073	0.292	-0.00127	-0.00967 – 0.00713	0.767
Random Effects						
σ^2	0.00227			0.71022		
τ_{00}	0.00042_{ID}			0.16866_{ID}		
ICC	0.15455			0.19191		
N	40_{ID}			40_{ID}		
Observations	19200			19200		
Marginal R^2 / Conditional R^2	0.029 / 0.179			0.685 / 0.746		
AIC	-62051.823			48182.856		

TABLE XIX: Control Group as reference.

	Training ErrorAbs			Training IntForceAbs		
Predictors	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*
(Intercept)	0.05978	0.05050 – 0.06906	**<0.001**	3.25180	3.06619 – 3.43741	**<0.001**
trIndex	-0.00093	-0.00104 – -0.00082	**<0.001**	-0.01607	-0.01805 – -0.01410	**<0.001**
LOC	-0.00630	-0.03008 – 0.01747	0.603	0.48641	0.01001 – 0.96282	**0.045**
Group [C]	0.00137	-0.01207 – 0.01482	0.841	-2.88070	-3.15015 – -2.61125	**<0.001**
wIndex	0.00071	0.00060 – 0.00083	**<0.001**	0.03146	0.02939 – 0.03353	**<0.001**
trIndex × LOC	0.00034	0.00005 – 0.00063	**0.021**	0.00269	-0.00240 – 0.00778	0.301
trIndex × Group [C]	0.00019	0.00003 – 0.00035	**0.023**	0.01235	0.00947 – 0.01523	**<0.001**
LOC × Group [C]	0.01560	-0.02362 – 0.05482	0.436	-0.54193	-1.32774 – 0.24388	0.176
(trIndex × LOC) × Group [C]	-0.00026	-0.00073 – 0.00022	0.292	0.00127	-0.00713 – 0.00967	0.767
Random Effects						
σ^2	0.00227			0.71022		
τ_{00}	0.00042_{ID}			0.16866_{ID}		
ICC	0.15455			0.19191		
N	40_{ID}			40_{ID}		
Observations	19200			19200		
Marginal R^2 / Conditional R^2	0.029 / 0.179			0.685 / 0.746		
AIC	-62051.823			48182.856		

TABLE XX: Experimental Group as reference.

Regression Results of Absolute Error and Interaction Force During Training in Non-Catch Sets (Equation 8). FDR Corrected.

	Training ErrorAbs			Training IntForceAbs		
Predictors	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*
(Intercept)	0.06115	0.05129 – 0.07101	**<0.001**	0.37110	0.17381 – 0.56839	**0.001**
trIndex	-0.00074	-0.00086 – -0.00062	**<0.001**	-0.00373	-0.00582 – -0.00163	**0.001**
LOC	0.00929	-0.02189 – 0.04048	0.719	-0.05552	-0.68044 – 0.56941	0.862
Group [E]	-0.00137	-0.01482 – 0.01207	0.841	2.88070	2.61125 – 3.15015	**<0.001**
wIndex	0.00071	0.00060 – 0.00083	**<0.001**	0.03146	0.02939 – 0.03353	**<0.001**
trIndex × LOC	0.00008	-0.00029 – 0.00046	0.749	0.00396	-0.00272 – 0.01064	0.316
trIndex × Group [E]	-0.00019	-0.00035 – -0.00003	0.052	-0.01235	-0.01523 – -0.00947	**<0.001**
LOC × Group [E]	-0.01560	-0.05482 – 0.02362	0.654	0.54193	-0.24388 – 1.32774	0.265
(trIndex × LOC) × Group [E]	0.00026	-0.00022 – 0.00073	0.526	-0.00127	-0.00967 – 0.00713	0.862
Random Effects						
σ^2	0.00227			0.71022		
τ_{00}	0.00042_{ID}			0.16866_{ID}		
ICC	0.15455			0.19191		
N	40_{ID}			40_{ID}		
Observations	19200			19200		
Marginal R^2 / Conditional R^2	0.029 / 0.179			0.685 / 0.746		
AIC	-62051.823			48182.856		

TABLE XXI: Control Group as reference.

	Training ErrorAbs			Training IntForceAbs		
Predictors	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*
(Intercept)	0.05978	0.05050 – 0.06906	**<0.001**	3.25180	3.06619 – 3.43741	**<0.001**
trIndex	-0.00093	-0.00104 – -0.00082	**<0.001**	-0.01607	-0.01805 – -0.01410	**<0.001**
LOC	-0.00630	-0.03008 – 0.01747	0.679	0.48641	0.01001 – 0.96282	0.068
Group [C]	0.00137	-0.01207 – 0.01482	0.841	-2.88070	-3.15015 – -2.61125	**<0.001**
wIndex	0.00071	0.00060 – 0.00083	**<0.001**	0.03146	0.02939 – 0.03353	**<0.001**
trIndex × LOC	0.00034	0.00005 – 0.00063	**0.042**	0.00269	-0.00240 – 0.00778	0.339
trIndex × Group [C]	0.00019	0.00003 – 0.00035	**0.042**	0.01235	0.00947 – 0.01523	**<0.001**
LOC × Group [C]	0.01560	-0.02362 – 0.05482	0.560	-0.54193	-1.32774 – 0.24388	0.227
(trIndex × LOC) × Group [C]	-0.00026	-0.00073 – 0.00022	0.438	0.00127	-0.00713 – 0.00967	0.767
Random Effects						
σ^2	0.00227			0.71022		
τ_{00}	0.00042_{ID}			0.16866_{ID}		
ICC	0.15455			0.19191		
N	40_{ID}			40_{ID}		
Observations	19200			19200		
Marginal R^2 / Conditional R^2	0.029 / 0.179			0.685 / 0.746		
AIC	-62051.823			48182.856		

TABLE XXII: Experimental Group as reference.

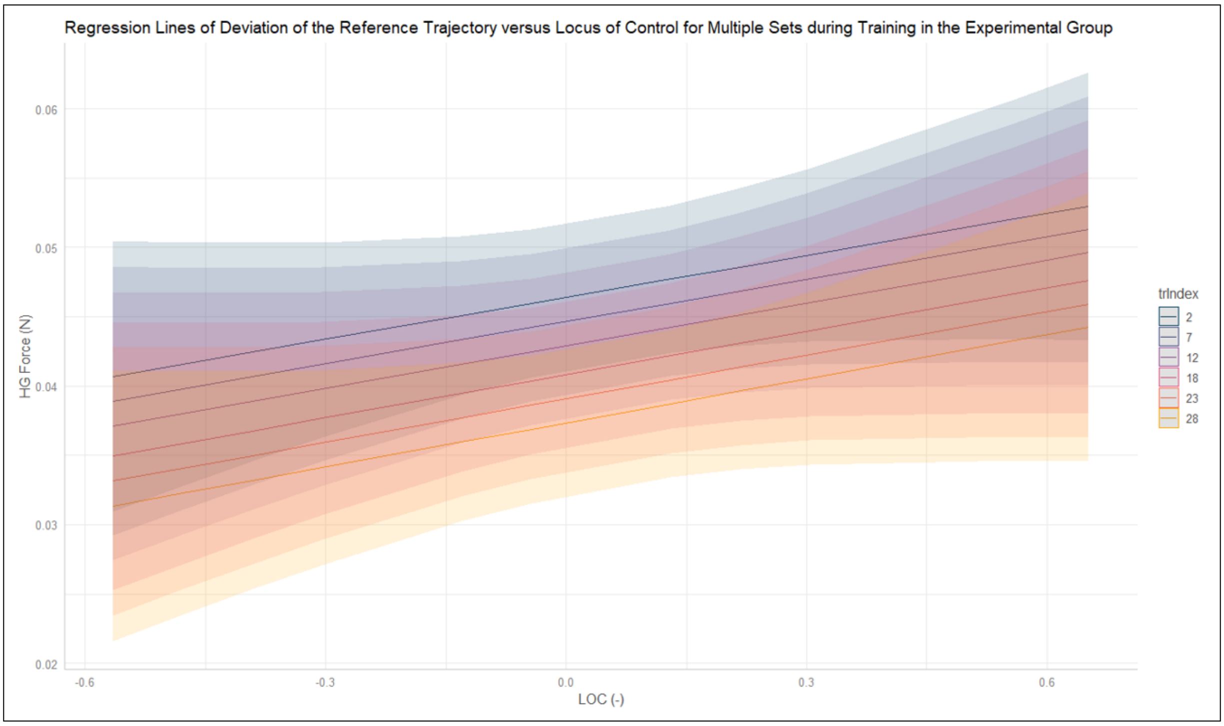

Fig. 20: Training regression lines of the $LOC * trIndex$ term (Equation 8, without the $Group$ variable), of a selection of the Experimental Training Sets ($trIndex$), shaded with their 95% confidence interval. **(A)** shows the Control Group and **(B)** the Experimental Group for the $AbsDevRef$ outcome metric.

Regression Results of the Deviation from the Reference Trajectory During Training in Non-Catch Sets for the Experimental Group (Equation 8, without the $Group$ term).

	Training DevRefAbs		
Predictors	*Estimates*	*CI*	*p*
(Intercept)	0.04096	0.03566 – 0.04627	**<0.001**
trIndex	-0.00035	-0.00041 – -0.00029	**<0.001**
LOC	0.01004	-0.00349 – 0.02357	0.146
wIndex	0.00065	0.00056 – 0.00073	**<0.001**
trIndex × LOC	0.00002	-0.00013 – 0.00017	0.798
Random Effects			
σ^2	0.00060		
$\tau_{00\ ID}$	0.00014		
ICC	0.18564		
N_{ID}	20		
Observations	9600		
Marginal R^2 / Conditional R^2	0.050 / 0.226		
AIC	-43862.468		

TABLE XXIII: Not FDR Corrected.

	Training DevRefAbs		
Predictors	*Estimates*	*CI*	*p*
(Intercept)	0.04096	0.03566 – 0.04627	**<0.001**
trIndex	-0.00035	-0.00041 – -0.00029	**<0.001**
LOC	0.01004	-0.00349 – 0.02357	0.182
wIndex	0.00065	0.00056 – 0.00073	**<0.001**
trIndex × LOC	0.00002	-0.00013 – 0.00017	0.798
Random Effects			
σ^2	0.00060		
$\tau_{00\ ID}$	0.00014		
ICC	0.18564		
N_{ID}	20		
Observations	9600		
Marginal R^2 / Conditional R^2	0.050 / 0.226		
AIC	-43862.468		

TABLE XXIV: FDR Corrected.

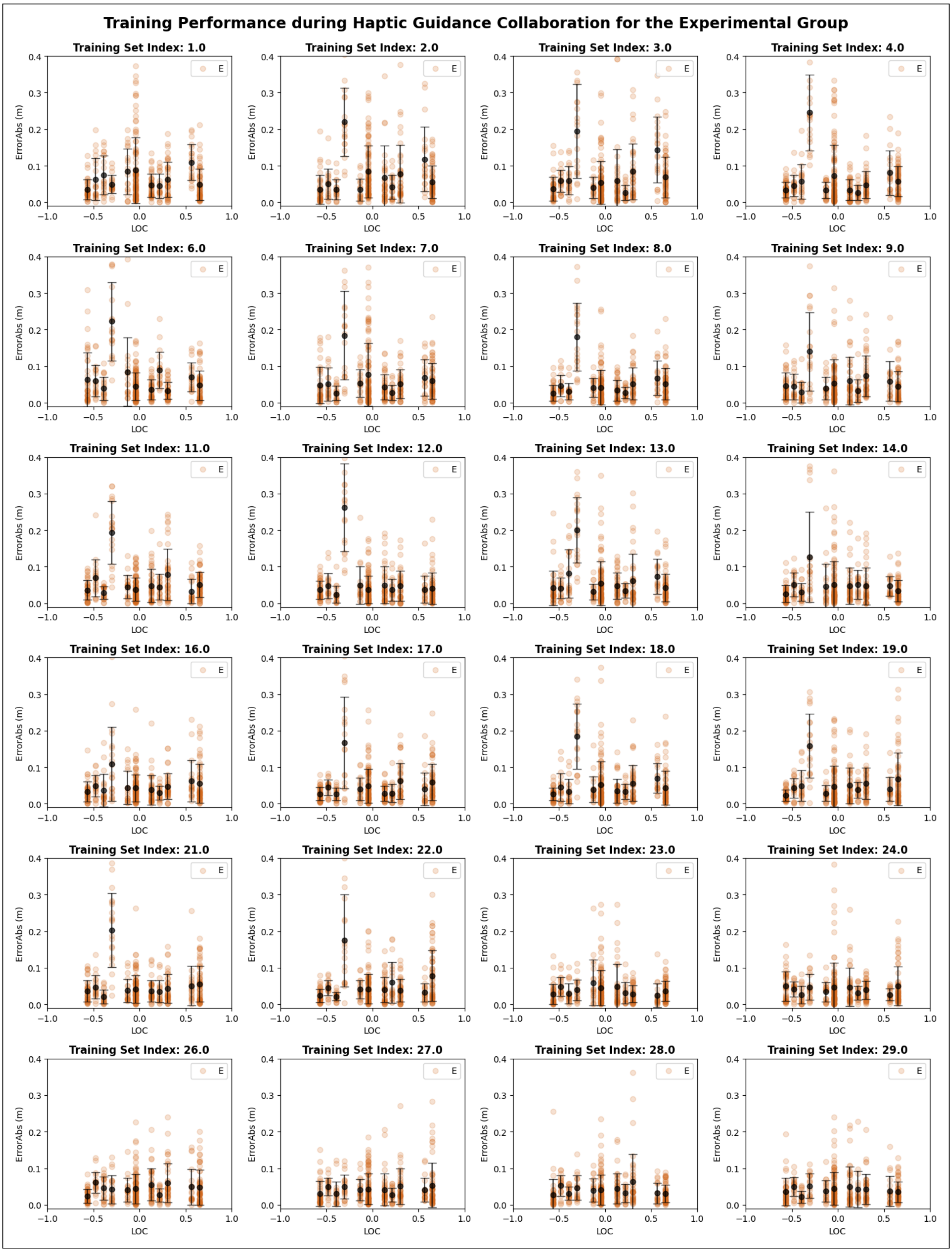

Fig. 21: Performance during training in non-Catch sets for the Experimental Group, i.e. during collaboration with the Haptic Guidance strategy. For each Locus of Control value, the Mean and Standard Deviation are shown over all targets and all participants with the respective Locus of Control value. One LOC value can contain multiple participants, according to the distribution in Figure 8-C (Appendix E).

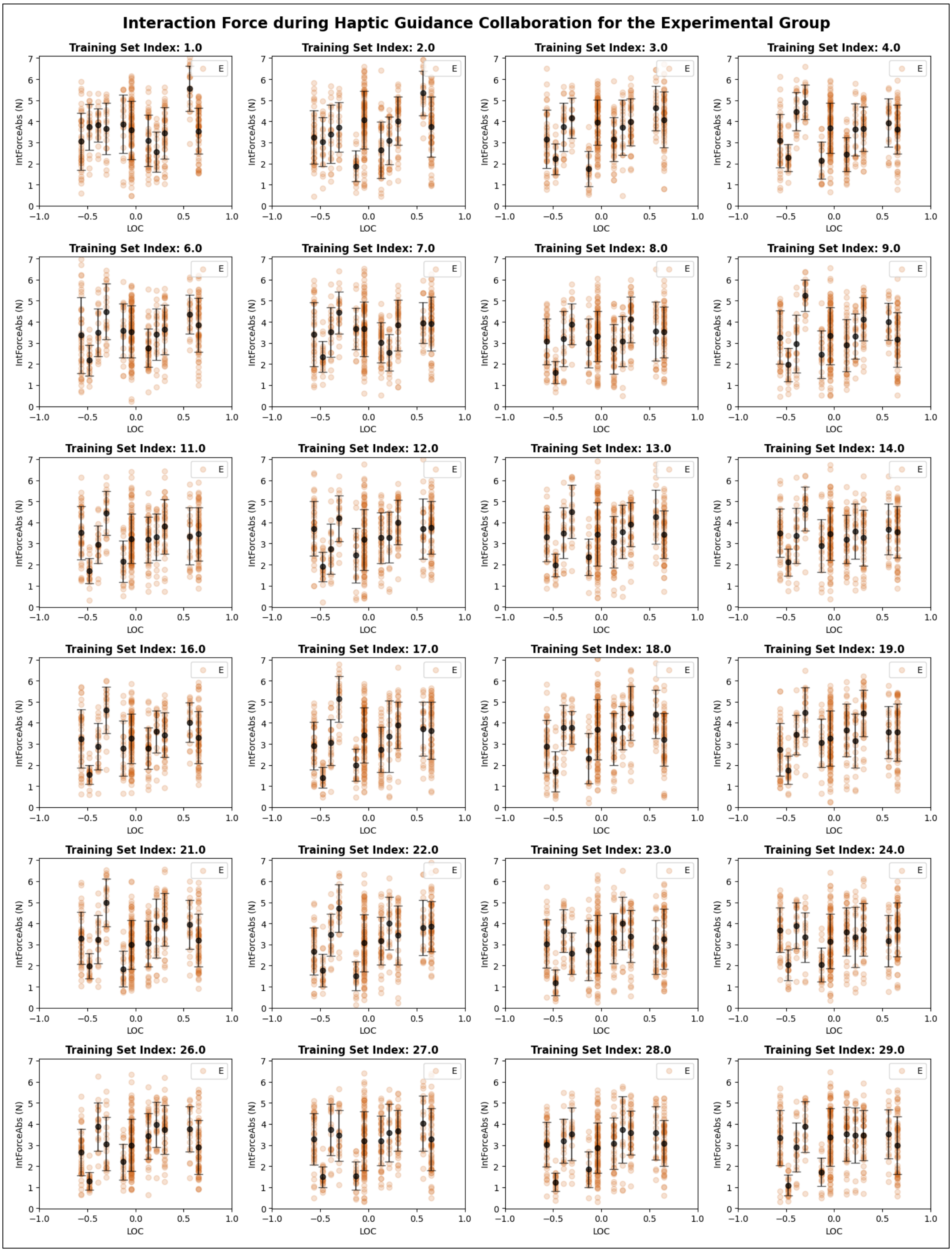

Fig. 22: Absolute Interaction Force during training in non-Catch sets for the Experimental Group, i.e. during collaboration with the Haptic Guidance strategy. For each Locus of Control value, the Mean and Standard Deviation are shown over all targets and all participants with the respective Locus of Control value. One LOC value can contain multiple participants, according to the distribution in Figure 8-C (Appendix E).

APPENDIX L
USER EXPERIENCE – SENSE OF AGENCY

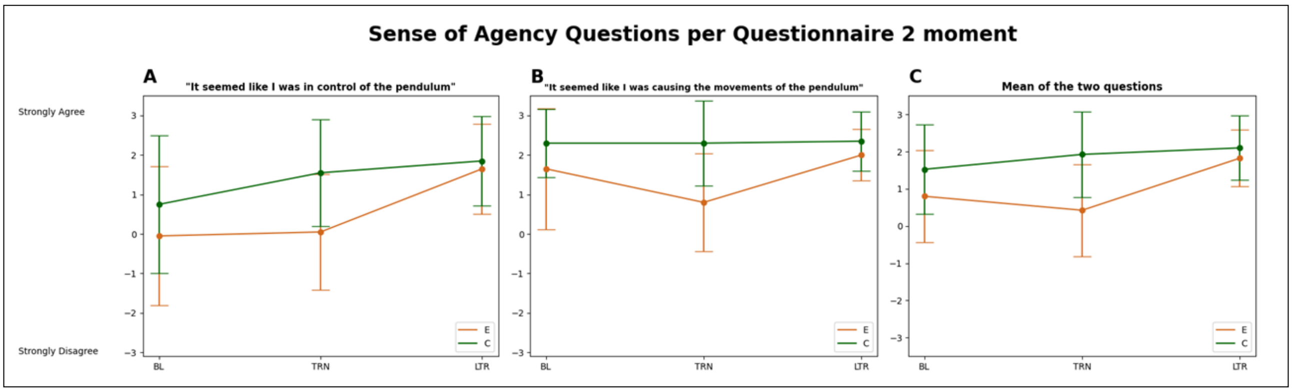

Fig. 23: Sense of Agency for each Questionnaire moment per Group, visualized by the mean and standard deviation of the answers per Questionnaire 2 moment. **(A)** Shows results for the Pendulum Control question, **(B)** for the Cause Movement question, and **(C)** the Mean of the two previous questions.

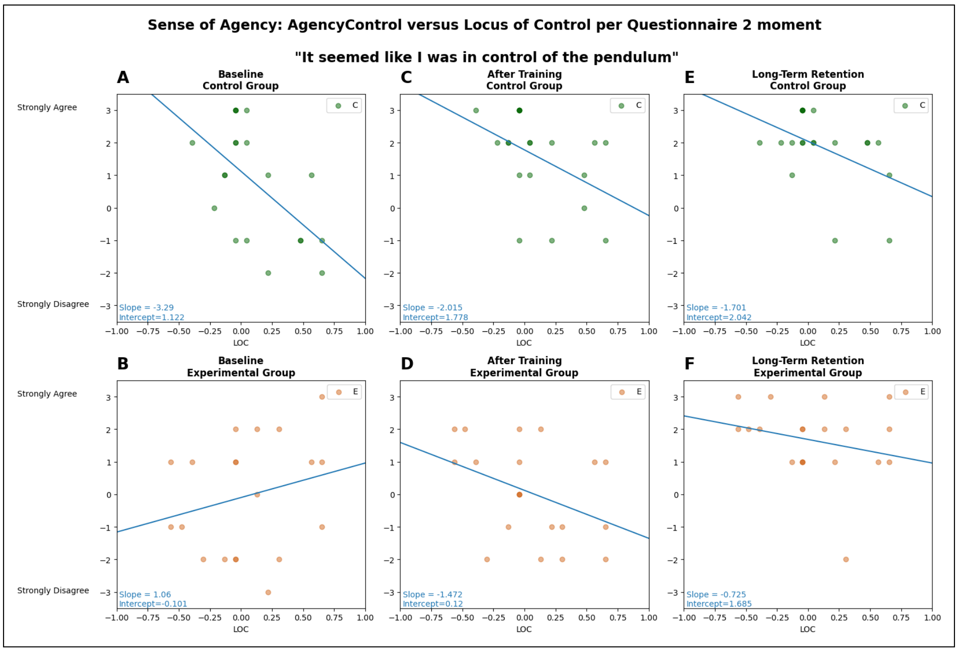

Fig. 24: Sense of Agency at different Questionnaire moments for the Pendulum Control question per Group. **(A-B)** At Baseline, **(C-D)** After Training, and **(E-F)** Long-Term Retention. Regression lines are shown in blue, with their respective slope and intercept estimates.

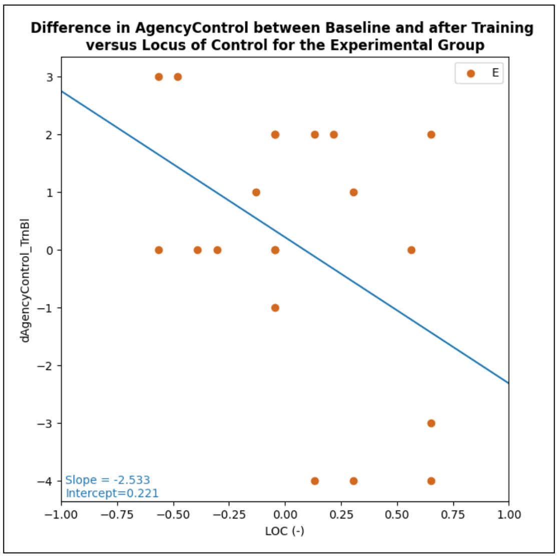

Fig. 25: Sense of Agency difference for the Question "*It seemed like I was in control of the pendulum*" versus Locus of Control for the Experimental Group. $AgencyControl$ scores of the same participant at Baseline were subtracted from those after Training to obtain $dAgencyControl_{TrnBl}$. The effect has a correlation coefficient (Pearson's r) of -0.440 with $p = 0.052$.

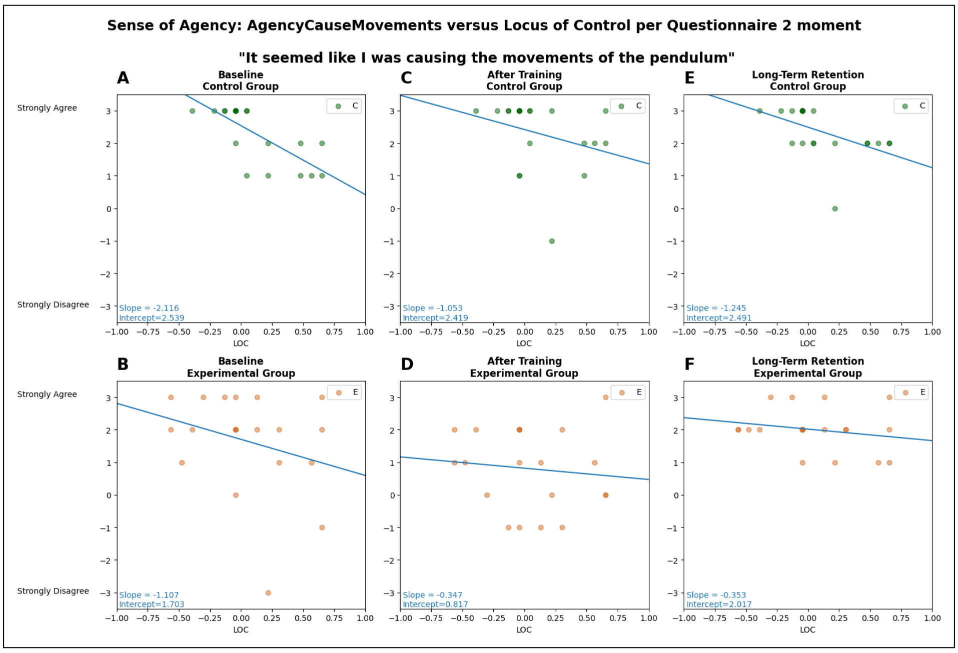

Fig. 26: Sense of Agency at different Questionnaire moments for the Cause Movements question per Group. **(A-B)** At Baseline, **(C-D)** after Training, and **(E-F)** at Long-Term Retention. Regression lines are shown in blue, with their respective slope and intercept estimates.

Regression Results of Sense of Agency (Equation 9), with the $AgencyControl$ and $AgencyCauseMovements$ questions, and their mean as separate dependent variables. Not FDR Corrected.

	AgencyControl			AgencyCauseMovements			AgencyMean		
Predictors	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*
(Intercept)	1.12	0.48 – 1.77	**0.001**	2.54	2.06 – 3.02	**<0.001**	1.83	1.35 – 2.31	**<0.001**
Group [E]	-1.22	-2.11 – -0.34	**0.007**	-0.84	-1.50 – -0.17	**0.014**	-1.03	-1.69 – -0.37	**0.003**
Quest [TRN]	0.66	-0.12 – 1.43	0.096	-0.12	-0.72 – 0.48	0.692	0.27	-0.33 – 0.86	0.374
Quest [LTR]	0.92	0.15 – 1.69	**0.020**	-0.05	-0.65 – 0.55	0.873	0.44	-0.16 – 1.03	0.149
LOC	-3.29	-5.35 – -1.23	**0.002**	-2.12	-3.66 – -0.57	**0.008**	-2.70	-4.24 – -1.16	**0.001**
Group [E] × Quest [TRN]	-0.43	-1.50 – 0.63	0.419	-0.77	-1.59 – 0.06	0.067	-0.60	-1.42 – 0.22	0.148
Group [E] × Quest [LTR]	0.87	-0.20 – 1.93	0.109	0.36	-0.46 – 1.18	0.384	0.61	-0.20 – 1.43	0.139
Group [E] × LOC	4.35	1.76 – 6.94	**0.001**	1.01	-0.93 – 2.95	0.305	2.68	0.74 – 4.62	**0.007**
Quest [TRN] × LOC	1.28	-1.19 – 3.74	0.307	1.06	-0.84 – 2.97	0.271	1.17	-0.72 – 3.06	0.223
Quest [LTR] × LOC	1.59	-0.87 – 4.05	0.204	0.87	-1.04 – 2.78	0.367	1.23	-0.66 – 3.12	0.200
(Group [E] × Quest [TRN]) × LOC	-3.81	-6.91 – -0.71	**0.016**	-0.30	-2.70 – 2.09	0.803	-2.06	-4.44 – 0.32	0.090
(Group [E] × Quest [LTR]) × LOC	-3.37	-6.47 – -0.28	**0.033**	-0.12	-2.51 – 2.28	0.924	-1.75	-4.13 – 0.63	0.149
Random Effects									
σ^2	1.33			0.79			0.78		
τ_{00}	0.52_{ID}			0.24_{ID}			0.25_{ID}		
ICC	0.28			0.23			0.25		
N	40_{ID}			40_{ID}			40_{ID}		
Observations	120			120			120		
Marginal R^2 / Conditional R^2	0.337 / 0.525			0.299 / 0.464			0.358 / 0.516		
AIC	416.021			355.938			355.397		

TABLE XXV: Control Group as reference.

	AgencyControl			AgencyCauseMovements			AgencyMean		
Predictors	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*
(Intercept)	-0.10	-0.71 – 0.51	0.743	1.70	1.25 – 2.16	**<0.001**	0.80	0.35 – 1.26	**0.001**
Group [C]	1.22	0.34 – 2.11	**0.007**	0.84	0.17 – 1.50	**0.014**	1.03	0.37 – 1.69	**0.003**
Quest [TRN]	0.22	-0.51 – 0.95	0.548	-0.89	-1.45 – -0.32	**0.002**	-0.33	-0.89 – 0.23	0.241
Quest [LTR]	1.79	1.06 – 2.51	**<0.001**	0.31	-0.25 – 0.88	0.271	1.05	0.49 – 1.61	**<0.001**
LOC	1.06	-0.51 – 2.63	0.183	-1.11	-2.28 – 0.07	0.064	-0.02	-1.20 – 1.15	0.968
Group [C] × Quest [TRN]	0.43	-0.63 – 1.50	0.419	0.77	-0.06 – 1.59	0.067	0.60	-0.22 – 1.42	0.148
Group [C] × Quest [LTR]	-0.87	-1.93 – 0.20	0.109	-0.36	-1.18 – 0.46	0.384	-0.61	-1.43 – 0.20	0.139
Group [C] × LOC	-4.35	-6.94 – -1.76	**0.001**	-1.01	-2.95 – 0.93	0.305	-2.68	-4.62 – -0.74	**0.007**
Quest [TRN] × LOC	-2.53	-4.41 – -0.65	**0.009**	0.76	-0.69 – 2.21	0.302	-0.89	-2.33 – 0.56	0.226
Quest [LTR] × LOC	-1.79	-3.66 – 0.09	0.062	0.75	-0.70 – 2.21	0.306	-0.52	-1.96 – 0.93	0.480
(Group [C] × Quest [TRN]) × LOC	3.81	0.71 – 6.91	**0.016**	0.30	-2.09 – 2.70	0.803	2.06	-0.32 – 4.44	0.090
(Group [C] × Quest [LTR]) × LOC	3.37	0.28 – 6.47	**0.033**	0.12	-2.28 – 2.51	0.924	1.75	-0.63 – 4.13	0.149
Random Effects									
σ^2	1.33			0.79			0.78		
τ_{00}	0.52_{ID}			0.24_{ID}			0.25_{ID}		
ICC	0.28			0.23			0.25		
N	40_{ID}			40_{ID}			40_{ID}		
Observations	120			120			120		
Marginal R^2 / Conditional R^2	0.337 / 0.525			0.299 / 0.464			0.358 / 0.516		
AIC	416.021			355.938			355.397		

TABLE XXVI: Experimental Group as reference.

Regression Results of Sense of Agency (Equation 9), with the two questions and their mean as separate dependent variables. FDR Corrected.

	AgencyControl			AgencyCauseMovements			AgencyMean		
Predictors	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*
(Intercept)	1.12	0.48 – 1.77	**0.007**	2.54	2.06 – 3.02	**<0.001**	1.83	1.35 – 2.31	**<0.001**
Group [E]	-1.22	-2.11 – -0.34	**0.022**	-0.84	-1.50 – -0.17	0.057	-1.03	-1.69 – -0.37	**0.011**
Quest [TRN]	0.66	-0.12 – 1.43	0.144	-0.12	-0.72 – 0.48	0.922	0.27	-0.33 – 0.86	0.374
Quest [LTR]	0.92	0.15 – 1.69	**0.041**	-0.05	-0.65 – 0.55	0.924	0.44	-0.16 – 1.03	0.199
LOC	-3.29	-5.35 – -1.23	**0.008**	-2.12	-3.66 – -0.57	**0.046**	-2.70	-4.24 – -1.16	**0.004**
Group [E] × Quest [TRN]	-0.43	-1.50 – 0.63	0.419	-0.77	-1.59 – 0.06	0.202	-0.60	-1.42 – 0.22	0.199
Group [E] × Quest [LTR]	0.87	-0.20 – 1.93	0.146	0.36	-0.46 – 1.18	0.576	0.61	-0.20 – 1.43	0.199
Group [E] × LOC	4.35	1.76 – 6.94	**0.007**	1.01	-0.93 – 2.95	0.576	2.68	0.74 – 4.62	**0.021**
Quest [TRN] × LOC	1.28	-1.19 – 3.74	0.335	1.06	-0.84 – 2.97	0.576	1.17	-0.72 – 3.06	0.244
Quest [LTR] × LOC	1.59	-0.87 – 4.05	0.245	0.87	-1.04 – 2.78	0.576	1.23	-0.66 – 3.12	0.240
(Group [E] × Quest [TRN]) × LOC	-3.81	-6.91 – -0.71	**0.040**	-0.30	-2.70 – 2.09	0.924	-2.06	-4.44 – 0.32	0.199
(Group [E] × Quest [LTR]) × LOC	-3.37	-6.47 – -0.28	0.057	-0.12	-2.51 – 2.28	0.924	-1.75	-4.13 – 0.63	0.199
Random Effects									
σ^2	1.33			0.79			0.78		
τ_{00}	0.52_{ID}			0.24_{ID}			0.25_{ID}		
ICC	0.28			0.23			0.25		
N	40_{ID}			40_{ID}			40_{ID}		
Observations	120			120			120		
Marginal R^2 / Conditional R^2	0.337 / 0.525			0.299 / 0.464			0.358 / 0.516		
AIC	416.021			355.938			355.397		

TABLE XXVII: Control Group as reference.

	AgencyControl			AgencyCauseMovements			AgencyMean		
Predictors	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*
(Intercept)	-0.10	-0.71 – 0.51	0.743	1.70	1.25 – 2.16	**<0.001**	0.80	0.35 – 1.26	**0.004**
Group [C]	1.22	0.34 – 2.11	**0.026**	0.84	0.17 – 1.50	0.057	1.03	0.37 – 1.69	**0.011**
Quest [TRN]	0.22	-0.51 – 0.95	0.598	-0.89	-1.45 – -0.32	**0.014**	-0.33	-0.89 – 0.23	0.289
Quest [LTR]	1.79	1.06 – 2.51	**<0.001**	0.31	-0.25 – 0.88	0.407	1.05	0.49 – 1.61	**0.004**
LOC	1.06	-0.51 – 2.63	0.244	-1.11	-2.28 – 0.07	0.162	-0.02	-1.20 – 1.15	0.968
Group [C] × Quest [TRN]	0.43	-0.63 – 1.50	0.503	0.77	-0.06 – 1.59	0.162	0.60	-0.22 – 1.42	0.223
Group [C] × Quest [LTR]	-0.87	-1.93 – 0.20	0.164	-0.36	-1.18 – 0.46	0.461	-0.61	-1.43 – 0.20	0.223
Group [C] × LOC	-4.35	-6.94 – -1.76	**0.007**	-1.01	-2.95 – 0.93	0.407	-2.68	-4.62 – -0.74	**0.021**
Quest [TRN] × LOC	-2.53	-4.41 – -0.65	**0.026**	0.76	-0.69 – 2.21	0.407	-0.89	-2.33 – 0.56	0.289
Quest [LTR] × LOC	-1.79	-3.66 – 0.09	0.107	0.75	-0.70 – 2.21	0.407	-0.52	-1.96 – 0.93	0.524
(Group [C] × Quest [TRN]) × LOC	3.81	0.71 – 6.91	**0.040**	0.30	-2.09 – 2.70	0.876	2.06	-0.32 – 4.44	0.215
(Group [C] × Quest [LTR]) × LOC	3.37	0.28 – 6.47	0.066	0.12	-2.28 – 2.51	0.924	1.75	-0.63 – 4.13	0.223
Random Effects									
σ^2	1.33			0.79			0.78		
τ_{00}	0.52_{ID}			0.24_{ID}			0.25_{ID}		
ICC	0.28			0.23			0.25		
N	40_{ID}			40_{ID}			40_{ID}		
Observations	120			120			120		
Marginal R^2 / Conditional R^2	0.337 / 0.525			0.299 / 0.464			0.358 / 0.516		
AIC	416.021			355.938			355.397		

TABLE XXVIII: Experimental Group as reference.

Appendix M
User Experience – Intrinsic Motivation

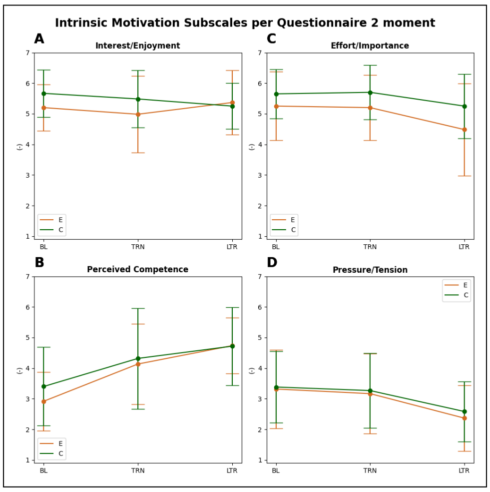

Fig. 27: Intrinsic Motivation at different 2 Questionnaire moments per Group for each of the following selected subscales: **(A)** $Interest/Enjoyment$, **(B)** $Perceived\ Competence$, **(C)** $Effort/Importance$, **(D)** $Pressure/Tension$.

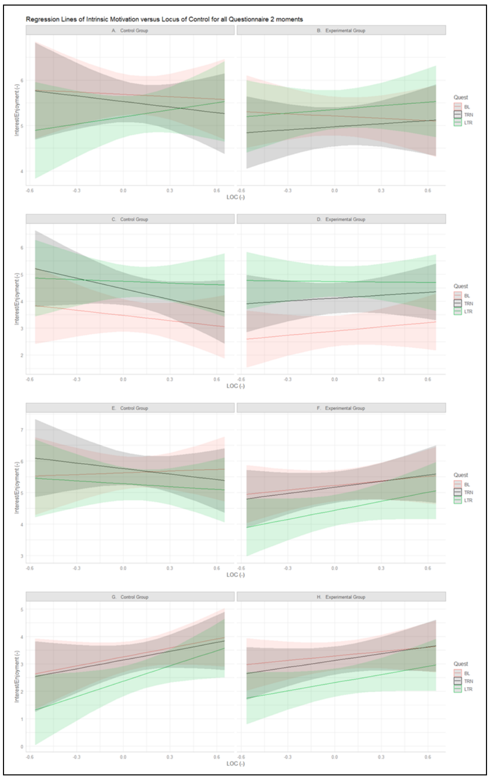

Fig. 28: User Experience regression lines of the $LOC * Quest * Group$ term (Equation 9) of the Intrinsic Motivation Inventory Subscales, shaded with their 95% confidence interval. **(A-B)** show $Interest/Enjoyment$, **(C-D)** $Perceived\ Competence$, **(E-F)** $Effort/Importance$ and **(G-H)** $Pressure/Tension$, with the Control Group left and the Experimental Group right.

Regression Results of Intrinsic Motivation (Equation 9), with the selected subscales of the Intrinsic Motivation Inventory as separate dependent variables. Not FDR Corrected.

	Interest/Enjoyment			Perceived Competence			Effort/Importance			Pressure/Tension		
Predictors	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*
(Intercept)	5.69	5.23 – 6.14	**<0.001**	3.47	2.87 – 4.08	**<0.001**	5.63	5.10 – 6.15	**<0.001**	3.26	2.71 – 3.81	**<0.001**
Group [E]	-0.48	-1.10 – 0.15	0.132	-0.58	-1.41 – 0.25	0.168	-0.40	-1.12 – 0.32	0.270	0.03	-0.72 – 0.78	0.935
Quest [TRN]	-0.16	-0.50 – 0.18	0.364	0.99	0.53 – 1.46	**<0.001**	0.14	-0.24 – 0.51	0.468	-0.11	-0.62 – 0.39	0.654
Quest [LTR]	-0.49	-0.83 – -0.15	**0.005**	1.27	0.80 – 1.73	**<0.001**	-0.35	-0.72 – 0.03	0.069	-0.89	-1.39 – -0.38	**0.001**
LOC	-0.17	-1.61 – 1.28	0.817	-0.64	-2.57 – 1.28	0.508	0.18	-1.49 – 1.85	0.829	1.09	-0.65 – 2.83	0.217
Group [E] × Quest [TRN]	-0.08	-0.55 – 0.39	0.736	0.23	-0.41 – 0.87	0.476	-0.19	-0.71 – 0.32	0.452	-0.05	-0.74 – 0.64	0.887
Group [E] × Quest [LTR]	0.64	0.17 – 1.11	**0.008**	0.58	-0.06 – 1.22	0.077	-0.44	-0.96 – 0.07	0.088	-0.08	-0.78 – 0.61	0.808
Group [E] × LOC	-0.00	-1.82 – 1.81	0.997	1.17	-1.25 – 3.59	0.341	0.30	-1.80 – 2.40	0.777	-0.55	-2.74 – 1.64	0.619
Quest [TRN] × LOC	-0.24	-1.32 – 0.84	0.662	-0.67	-2.16 – 0.81	0.370	-0.77	-1.95 – 0.42	0.203	-0.02	-1.63 – 1.58	0.977
Quest [LTR] × LOC	0.69	-0.39 – 1.77	0.208	0.44	-1.05 – 1.92	0.563	-0.49	-1.67 – 0.70	0.418	0.77	-0.84 – 2.37	0.345
(Group [E] × Quest [TRN]) × LOC	0.64	-0.72 – 2.00	0.355	0.51	-1.36 – 2.38	0.589	0.93	-0.56 – 2.42	0.217	0.31	-1.70 – 2.33	0.759
(Group [E] × Quest [LTR]) × LOC	-0.25	-1.61 – 1.12	0.721	-1.02	-2.89 – 0.85	0.283	0.96	-0.53 – 2.45	0.204	-0.32	-2.33 – 1.70	0.756
Random Effects												
σ^2	0.26			0.48			0.31			0.56		
τ_{00}	0.66_{ID}			1.13_{ID}			0.91_{ID}			0.76_{ID}		
ICC	0.72			0.70			0.75			0.58		
N	40_{ID}			40_{ID}			40_{ID}			40_{ID}		
Observations	120			120			120			120		
Marginal R^2 / Conditional R^2	0.060 / 0.736			0.234 / 0.771			0.144 / 0.785			0.178 / 0.652		
AIC	288.037			353.810			312.343			353.336		

TABLE XXIX: Control Group as reference.

	Interest/Enjoyment			Perceived Competence			Effort/Importance			Pressure/Tension		
Predictors	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*
(Intercept)	5.21	4.78 – 5.63	**<0.001**	2.89	2.32 – 3.46	**<0.001**	5.23	4.73 – 5.72	**<0.001**	3.29	2.78 – 3.80	**<0.001**
Group [C]	0.48	-0.15 – 1.10	0.132	0.58	-0.25 – 1.41	0.168	0.40	-0.32 – 1.12	0.270	-0.03	-0.78 – 0.72	0.935
Quest [TRN]	-0.24	-0.56 – 0.08	0.147	1.22	0.79 – 1.66	**<0.001**	-0.06	-0.41 – 0.29	0.743	-0.16	-0.64 – 0.31	0.494
Quest [LTR]	0.15	-0.17 – 0.47	0.369	1.84	1.41 – 2.28	**<0.001**	-0.79	-1.14 – -0.44	**<0.001**	-0.97	-1.44 – -0.50	**<0.001**
LOC	-0.17	-1.27 – 0.93	0.757	0.52	-0.94 – 1.99	0.482	0.48	-0.79 – 1.76	0.454	0.54	-0.79 – 1.87	0.422
Group [C] × Quest [TRN]	0.08	-0.39 – 0.55	0.736	-0.23	-0.87 – 0.41	0.476	0.19	-0.32 – 0.71	0.452	0.05	-0.64 – 0.74	0.887
Group [C] × Quest [LTR]	-0.64	-1.11 – -0.17	**0.008**	-0.58	-1.22 – 0.06	0.077	0.44	-0.07 – 0.96	0.088	0.08	-0.61 – 0.78	0.808
Group [C] × LOC	0.00	-1.81 – 1.82	0.997	-1.17	-3.59 – 1.25	0.341	-0.30	-2.40 – 1.80	0.777	0.55	-1.64 – 2.74	0.619
Quest [TRN] × LOC	0.40	-0.43 – 1.22	0.340	-0.16	-1.30 – 0.97	0.776	0.17	-0.74 – 1.07	0.713	0.29	-0.93 – 1.51	0.640
Quest [LTR] × LOC	0.45	-0.38 – 1.27	0.286	-0.58	-1.72 – 0.55	0.310	0.47	-0.43 – 1.38	0.301	0.45	-0.77 – 1.67	0.467
(Group [C] × Quest [TRN]) × LOC	-0.64	-2.00 – 0.72	0.355	-0.51	-2.38 – 1.36	0.589	-0.93	-2.42 – 0.56	0.217	-0.31	-2.33 – 1.70	0.759
(Group [C] × Quest [LTR]) × LOC	0.25	-1.12 – 1.61	0.721	1.02	-0.85 – 2.89	0.283	-0.96	-2.45 – 0.53	0.204	0.32	-1.70 – 2.33	0.756
Random Effects												
σ^2	0.26			0.48			0.31			0.56		
τ_{00}	0.66_{ID}			1.13_{ID}			0.91_{ID}			0.76_{ID}		
ICC	0.72			0.70			0.75			0.58		
N	40_{ID}			40_{ID}			40_{ID}			40_{ID}		
Observations	120			120			120			120		
Marginal R^2 / Conditional R^2	0.060 / 0.736			0.234 / 0.771			0.144 / 0.785			0.178 / 0.652		
AIC	288.037			353.810			312.343			353.336		

TABLE XXX: Experimental Group as reference.

Regression Results of Intrinsic Motivation (Equation 9), with the selected subscales of the Intrinsic Motivation Inventory as separate dependent variables. FDR Corrected.

	Interest/Enjoyment			Perceived Competence			Effort/Importance			Pressure/Tension		
Predictors	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*
(Intercept)	5.69	5.23 – 6.14	**<0.001**	3.47	2.87 – 4.08	**<0.001**	5.63	5.10 – 6.15	**<0.001**	3.26	2.71 – 3.81	**<0.001**
Group [E]	-0.48	-1.10 – 0.15	0.395	-0.58	-1.41 – 0.25	0.402	-0.40	-1.12 – 0.32	0.463	0.03	-0.72 – 0.78	0.977
Quest [TRN]	-0.16	-0.50 – 0.18	0.625	0.99	0.53 – 1.46	**<0.001**	0.14	-0.24 – 0.51	0.562	-0.11	-0.62 – 0.39	0.977
Quest [LTR]	-0.49	-0.83 – -0.15	**0.028**	1.27	0.80 – 1.73	**<0.001**	-0.35	-0.72 – 0.03	0.351	-0.89	-1.39 – -0.38	**0.004**
LOC	-0.17	-1.61 – 1.28	0.892	-0.64	-2.57 – 1.28	0.589	0.18	-1.49 – 1.85	0.829	1.09	-0.65 – 2.83	0.868
Group [E] × Quest [TRN]	-0.08	-0.55 – 0.39	0.884	0.23	-0.41 – 0.87	0.589	-0.19	-0.71 – 0.32	0.562	-0.05	-0.74 – 0.64	0.977
Group [E] × Quest [LTR]	0.64	0.17 – 1.11	**0.031**	0.58	-0.06 – 1.22	0.231	-0.44	-0.96 – 0.07	0.351	-0.08	-0.78 – 0.61	0.977
Group [E] × LOC	-0.00	-1.82 – 1.81	0.997	1.17	-1.25 – 3.59	0.555	0.30	-1.80 – 2.40	0.829	-0.55	-2.74 – 1.64	0.977
Quest [TRN] × LOC	-0.24	-1.32 – 0.84	0.884	-0.67	-2.16 – 0.81	0.555	-0.77	-1.95 – 0.42	0.433	-0.02	-1.63 – 1.58	0.977
Quest [LTR] × LOC	0.69	-0.39 – 1.77	0.499	0.44	-1.05 – 1.92	0.589	-0.49	-1.67 – 0.70	0.562	0.77	-0.84 – 2.37	0.977
(Group [E] × Quest [TRN]) × LOC	0.64	-0.72 – 2.00	0.625	0.51	-1.36 – 2.38	0.589	0.93	-0.56 – 2.42	0.433	0.31	-1.70 – 2.33	0.977
(Group [E] × Quest [LTR]) × LOC	-0.25	-1.61 – 1.12	0.884	-1.02	-2.89 – 0.85	0.555	0.96	-0.53 – 2.45	0.433	-0.32	-2.33 – 1.70	0.977
Random Effects												
σ^2	0.26			0.48			0.31			0.56		
τ_{00}	0.66_{ID}			1.13_{ID}			0.91_{ID}			0.76_{ID}		
ICC	0.72			0.70			0.75			0.58		
N	40_{ID}			40_{ID}			40_{ID}			40_{ID}		
Observations	120			120			120			120		
Marginal R^2 / Conditional R^2	0.060 / 0.736			0.234 / 0.771			0.144 / 0.785			0.178 / 0.652		
AIC	288.037			353.810			312.343			353.336		

TABLE XXXI: Control Group as reference.

	Interest/Enjoyment			Perceived Competence			Effort/Importance			Pressure/Tension		
Predictors	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*
(Intercept)	5.21	4.78 – 5.63	**<0.001**	2.89	2.32 – 3.46	**<0.001**	5.23	4.73 – 5.72	**<0.001**	3.29	2.78 – 3.80	**<0.001**
Group [C]	0.48	-0.15 – 1.10	0.440	0.58	-0.25 – 1.41	0.402	0.40	-0.32 – 1.12	0.516	-0.03	-0.78 – 0.72	0.935
Quest [TRN]	-0.24	-0.56 – 0.08	0.440	1.22	0.79 – 1.66	**<0.001**	-0.06	-0.41 – 0.29	0.777	-0.16	-0.64 – 0.31	0.935
Quest [LTR]	0.15	-0.17 – 0.47	0.554	1.84	1.41 – 2.28	**<0.001**	-0.79	-1.14 – -0.44	**<0.001**	-0.97	-1.44 – -0.50	**0.001**
LOC	-0.17	-1.27 – 0.93	0.825	0.52	-0.94 – 1.99	0.578	0.48	-0.79 – 1.76	0.605	0.54	-0.79 – 1.87	0.935
Group [C] × Quest [TRN]	0.08	-0.39 – 0.55	0.825	-0.23	-0.87 – 0.41	0.578	0.19	-0.32 – 0.71	0.605	0.05	-0.64 – 0.74	0.935
Group [C] × Quest [LTR]	-0.64	-1.11 – -0.17	**0.046**	-0.58	-1.22 – 0.06	0.231	0.44	-0.07 – 0.96	0.351	0.08	-0.61 – 0.78	0.935
Group [C] × LOC	0.00	-1.81 – 1.82	0.997	-1.17	-3.59 – 1.25	0.512	-0.30	-2.40 – 1.80	0.777	0.55	-1.64 – 2.74	0.935
Quest [TRN] × LOC	0.40	-0.43 – 1.22	0.554	-0.16	-1.30 – 0.97	0.776	0.17	-0.74 – 1.07	0.777	0.29	-0.93 – 1.51	0.935
Quest [LTR] × LOC	0.45	-0.38 – 1.27	0.554	-0.58	-1.72 – 0.55	0.512	0.47	-0.43 – 1.38	0.516	0.45	-0.77 – 1.67	0.935
(Group [C] × Quest [TRN]) × LOC	-0.64	-2.00 – 0.72	0.554	-0.51	-2.38 – 1.36	0.642	-0.93	-2.42 – 0.56	0.516	-0.31	-2.33 – 1.70	0.935
(Group [C] × Quest [LTR]) × LOC	0.25	-1.12 – 1.61	0.825	1.02	-0.85 – 2.89	0.512	-0.96	-2.45 – 0.53	0.516	0.32	-1.70 – 2.33	0.935
Random Effects												
σ^2	0.26			0.48			0.31			0.56		
τ_{00}	0.66_{ID}			1.13_{ID}			0.91_{ID}			0.76_{ID}		
ICC	0.72			0.70			0.75			0.58		
N	40_{ID}			40_{ID}			40_{ID}			40_{ID}		
Observations	120			120			120			120		
Marginal R^2 / Conditional R^2	0.060 / 0.736			0.234 / 0.771			0.144 / 0.785			0.178 / 0.652		
AIC	288.037			353.810			312.343			353.336		

TABLE XXXII: Experimental Group as reference.

Appendix N
User Experience – Robot Interaction & Locus of Control

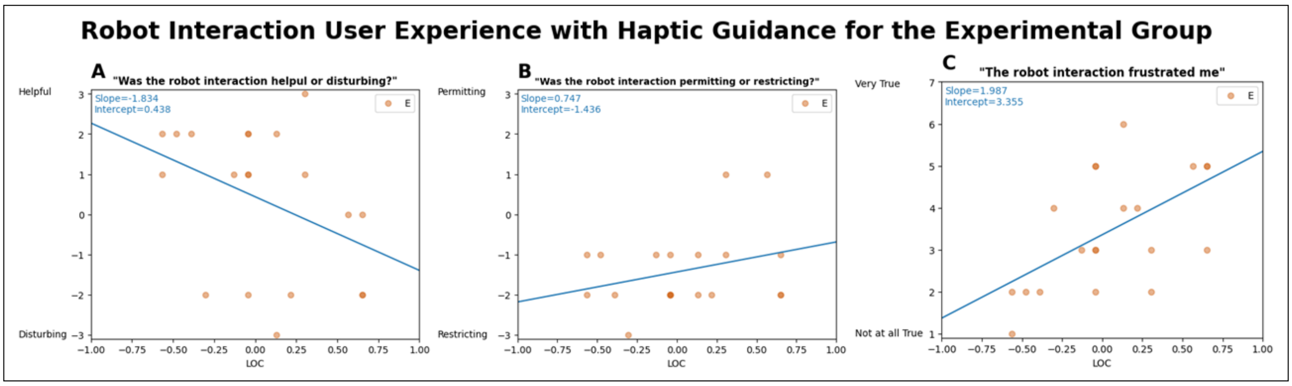

Fig. 29: User Experience with respect to our Haptic Guidance strategy based on Locus of Control tendency, for **(A)** Perceived Helpfulness (with mean 0.35, standard deviation 1.84), **(B)** Perceived Restrictiveness (with mean -1.40, standard deviation 0.99) and **(C)** Perceived Frustration (with mean 3.45, standard deviation 1.39). The regression lines represent the linear relation between User Experience and Locus of Control in blue, with their respective estimates for the slope and intercept.

Regression Results of the Robot Interaction User Experience after Training with Haptic Guidance for the Experimental Group (Equation 10 with $Disturbing\ vs.\ Helpfull$**,** $Restricting\ vs.\ Permitting$ **or** $Frustration$ **as dependent variable.**

	Disturbing vs. Helpful			Restricting vs. Permitting			Frustration		
Predictors	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*
(Intercept)	0.44	-0.39 – 1.26	0.279	-1.44	-1.90 – -0.97	**<0.001**	3.35	2.79 – 3.92	**<0.001**
LOC	-1.83	-3.96 – 0.29	0.087	0.75	-0.45 – 1.94	0.205	1.99	0.54 – 3.44	**0.010**
Observations	20			20			20		
R^2 / R^2 adjusted	0.154 / 0.107			0.088 / 0.037			0.316 / 0.278		
AIC	82.846			59.683			67.442		

TABLE XXXIII: Not FDR Corrected.

	Disturbing vs. Helpful			Restricting vs. Permitting			Frustration		
Predictors	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*
(Intercept)	0.44	-0.39 – 1.26	0.279	-1.44	-1.90 – -0.97	**<0.001**	3.35	2.79 – 3.92	**<0.001**
LOC	-1.83	-3.96 – 0.29	0.174	0.75	-0.45 – 1.94	0.205	1.99	0.54 – 3.44	**0.010**
Observations	20			20			20		
R^2 / R^2 adjusted	0.154 / 0.107			0.088 / 0.037			0.316 / 0.278		
AIC	82.846			59.683			67.442		

TABLE XXXIV: FDR Corrected.

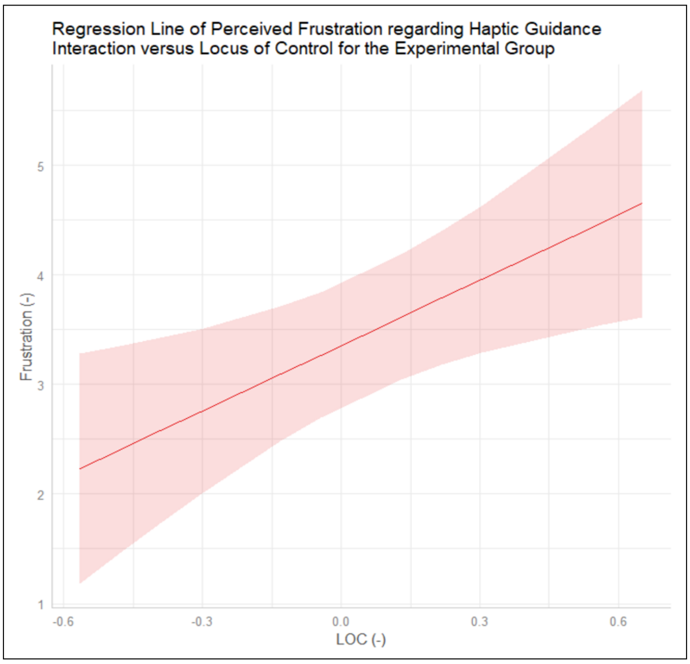

Fig. 30: Frustration regression line of the LOC term after Training (Equation 10), shaded with its 95% confidence interval. Pearson correlation coefficient equals 0.562 ($p = 0.0099$).

Appendix O
Additional Analyses

For the definitions of the variables used in this Appendix, we refer the reader to Appendix F. The analyses in this Appendix are only exploratory, and as such, their results and significance should be used with caution.

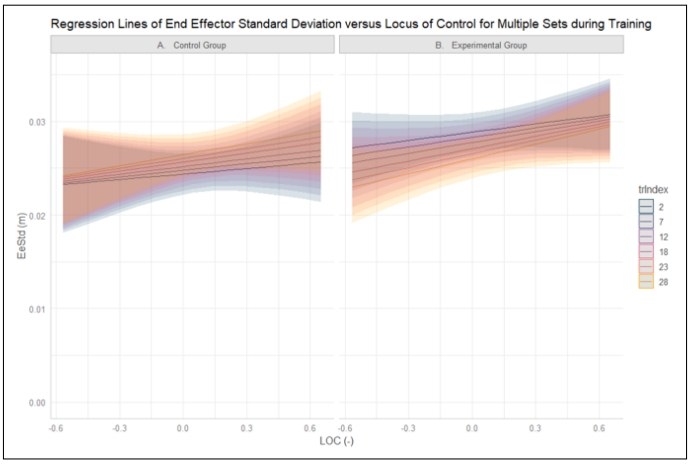

Fig. 31: End-Effector Standard Deviation regression lines of the $LOC * trIndex * Group$ term during Training (Equation 8) of a selection of the Experimental Training Sets ($trIndex$), shaded with their 95% confidence interval. **(A)** shows the Control Group and **(B)** the Experimental Group.

Regression Results of End-Effector Standard Deviation during Training (Equation 8 with $EeStd$ as dependent variable). Not FDR Corrected.

	Training EeStd		
Predictors	*Estimates*	*CI*	*p*
(Intercept)	0.01636	0.01412 – 0.01860	**<0.001**
trIndex	0.00008	0.00004 – 0.00012	**<0.001**
LOC	0.00181	-0.00521 – 0.00884	0.613
Group [E]	0.00484	0.00181 – 0.00787	**0.002**
wIndex	0.00083	0.00079 – 0.00087	**<0.001**
trIndex × LOC	0.00008	-0.00006 – 0.00021	0.267
trIndex × Group [E]	-0.00019	-0.00025 – -0.00013	**<0.001**
LOC × Group [E]	0.00093	-0.00791 – 0.00976	0.837
(trIndex × LOC) × Group [E]	0.00002	-0.00015 – 0.00018	0.838
Random Effects			
σ^2	0.00028		
$\tau_{00\ ID}$	0.00002		
ICC	0.06568		
N_{ID}	40		
Observations	19200		
Marginal R^2 / Conditional R^2	0.080 / 0.140		
AIC	-102247.284		

TABLE XXXV: Control Group as reference.

	Training EeStd		
Predictors	*Estimates*	*CI*	*p*
(Intercept)	0.02120	0.01909 – 0.02331	**<0.001**
trIndex	-0.00011	-0.00015 – -0.00007	**<0.001**
LOC	0.00274	-0.00262 – 0.00810	0.316
Group [C]	-0.00484	-0.00787 – -0.00181	**0.002**
wIndex	0.00083	0.00079 – 0.00087	**<0.001**
trIndex × LOC	0.00009	-0.00001 – 0.00019	0.073
trIndex × Group [C]	0.00019	0.00013 – 0.00025	**<0.001**
LOC × Group [C]	-0.00093	-0.00976 – 0.00791	0.837
(trIndex × LOC) × Group [C]	-0.00002	-0.00018 – 0.00015	0.838
Random Effects			
σ^2	0.00028		
$\tau_{00\ ID}$	0.00002		
ICC	0.06568		
N_{ID}	40		
Observations	19200		
Marginal R^2 / Conditional R^2	0.080 / 0.140		
AIC	-102247.284		

TABLE XXXVI: Experimental Group as reference.

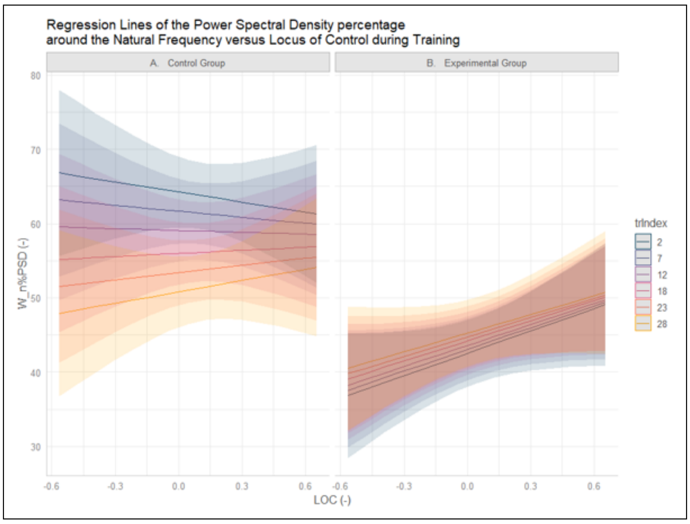

Fig. 32: Power Spectral Density around the Natural Frequency regression lines of the $LOC * trIndex * Group$ term during Training. Equation 8 was used, without $wIndex$ term. A selection of the Experimental Training Sets ($trIndex$) are visualized, shaded with their 95% confidence interval. **(A)** shows the Control Group and **(B)** the Experimental Group.

Regression Results of Power Spectral Density percentage around Natural Frequency during Training (Equation 8 with $\omega_N \%PSD$ as dependent variable, without $wIndex$ as independent variable). Not FDR Corrected.

	Training W_n%PSD		
Predictors	*Estimates*	*CI*	*p*
(Intercept)	65.27841	60.34307 – 70.21374	**<0.001**
LOC	-5.27410	-20.98530 – 10.43709	0.510
Group [E]	-22.96111	-29.73524 – -16.18698	**<0.001**
trIndex	-0.51712	-0.69634 – -0.33790	**<0.001**
LOC × Group [E]	15.47653	-4.27932 – 35.23237	0.125
LOC × trIndex	0.37026	-0.20027 – 0.94078	0.203
Group [E] × trIndex	0.62184	0.37585 – 0.86783	**<0.001**
(LOC × Group [E]) × trIndex	-0.43515	-1.15255 – 0.28224	0.234
Random Effects			
σ^2	258.45010		
τ_{00} ID	66.67222		
ICC	0.20507		
N ID	40		
Observations	960		
Marginal R^2 / Conditional R^2	0.154 / 0.328		
AIC	8138.642		

TABLE XXXVII: Control Group as reference.

	Training W_n%PSD		
Predictors	*Estimates*	*CI*	*p*
(Intercept)	42.31729	37.67711 – 46.95748	**<0.001**
LOC	10.20242	-1.77471 – 22.17956	0.095
Group [C]	22.96111	16.18698 – 29.73524	**<0.001**
trIndex	0.10471	-0.06379 – 0.27321	0.223
LOC × Group [C]	-15.47653	-35.23237 – 4.27932	0.125
LOC × trIndex	-0.06490	-0.49983 – 0.37003	0.770
Group [C] × trIndex	-0.62184	-0.86783 – -0.37585	**<0.001**
(LOC × Group [C]) × trIndex	0.43515	-0.28224 – 1.15255	0.234
Random Effects			
σ^2	258.45010		
τ_{00} ID	66.67222		
ICC	0.20507		
N ID	40		
Observations	960		
Marginal R^2 / Conditional R^2	0.154 / 0.328		
AIC	8138.642		

TABLE XXXVIII: Experimental Group as reference.

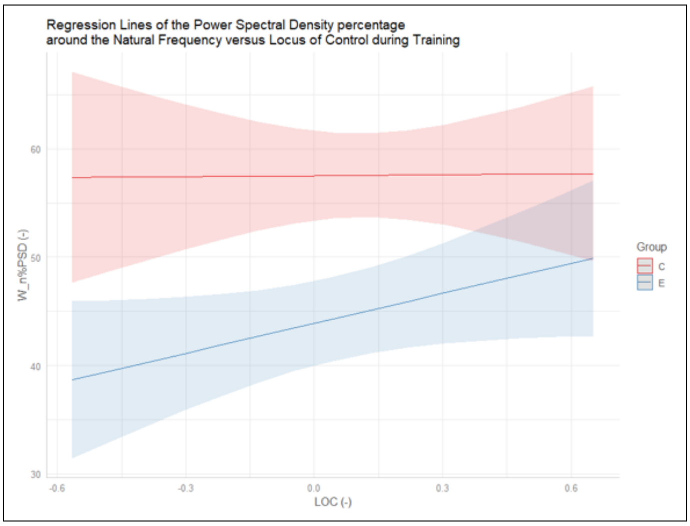

Fig. 33: Power Spectral Density around the Natural Frequency regression lines of the $LOC * Group$ term during Training. Equation 8 was used, without $wIndex$ term and $trIndex$ term, to visualize the fixed effect of the Locus of Control throughout Training. This results in a regression line for the Control Group (red) and the Experimental Group (blue) shaded with their 95% confidence interval.

Regression Results of Power Spectral Density percentage around Natural Frequency during Training (Equation 8 with $\omega_N\%PSD$ as dependent variable, but without $wIndex$ and $trIndex$ as independent variables). Not FDR Corrected.

	Training W_n%PSD (no trIndex)		
Predictors	*Estimates*	*CI*	*p*
(Intercept)	60.32400	55.81289 – 64.83510	**<0.001**
LOC	0.27976	-12.89610 – 13.45562	0.967
Group [E]	-13.63357	-19.31455 – -7.95259	**<0.001**
trIndex	-0.18683	-0.30645 – -0.06721	**0.002**
LOC × Group [E]	8.94921	-7.61861 – 25.51703	0.289
Random Effects			
σ^2	264.53241		
$\tau_{00\ ID}$	66.41878		
ICC	0.20069		
N_{ID}	40		
Observations	960		
Marginal R^2 / Conditional R^2	0.137 / 0.310		
AIC	8152.816		

TABLE XXXIX: Control Group as reference.

	Training W_n%PSD (no trIndex)		
Predictors	*Estimates*	*CI*	*p*
(Intercept)	46.69043	42.40530 – 50.97557	**<0.001**
LOC	9.22897	-0.81540 – 19.27334	0.072
Group [C]	13.63357	7.95259 – 19.31455	**<0.001**
trIndex	-0.18683	-0.30645 – -0.06721	**0.002**
LOC × Group [C]	-8.94921	-25.51703 – 7.61861	0.289
Random Effects			
σ^2	264.53241		
$\tau_{00\ ID}$	66.41878		
ICC	0.20069		
N_{ID}	40		
Observations	960		
Marginal R^2 / Conditional R^2	0.137 / 0.310		
AIC	8152.816		

TABLE XL: Experimental Group as reference.

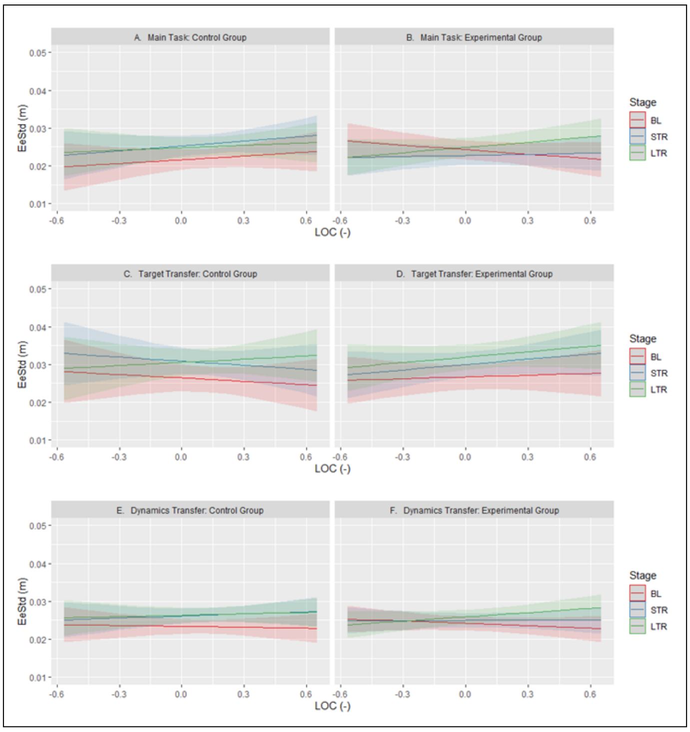

Fig. 34: End-Effector Standard Deviation regression lines of the $LOC * Stage * Group$ term during Assessment Tests, shaded with their 95% confidence interval. Equation 7 is used with $EeStd$ as dependent variable (see F). Each row shows a different Pendulum Task: **(A-B)** the Main Task, **(C-D)** the Target Transfer and **(E-F)** the Dynamics Transfer, with the first column the Control Group and the second column the Experimental Group.

Regression Results of End-Effector Standard Deviation during Assessment Tests (Equation 7 with $EeStd$ as dependent variable). Not FDR Corrected.

	Main Task EeStd			Target Transfer EeStd			Dynamics Transfer EeStd		
Predictors	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*
(Intercept)	0.01389	0.01106 – 0.01671	**<0.001**	0.02070	0.01701 – 0.02440	**<0.001**	0.01831	0.01616 – 0.02046	**<0.001**
LOC	0.00335	-0.00525 – 0.01194	0.445	-0.00299	-0.01432 – 0.00834	0.605	-0.00074	-0.00704 – 0.00555	0.817
Stage [STR]	0.00361	0.00200 – 0.00522	**<0.001**	0.00444	0.00254 – 0.00634	**<0.001**	0.00276	0.00112 – 0.00439	**0.001**
Stage [LTR]	0.00321	0.00160 – 0.00482	**<0.001**	0.00414	0.00224 – 0.00604	**<0.001**	0.00295	0.00131 – 0.00458	**<0.001**
Group [E]	0.00267	-0.00103 – 0.00637	0.158	0.00027	-0.00461 – 0.00516	0.913	0.00076	-0.00196 – 0.00347	0.585
sIndex	0.00248	0.00162 – 0.00335	**<0.001**	0.00282	0.00180 – 0.00385	**<0.001**	-0.00045	-0.00133 – 0.00043	0.314
wIndex	0.00068	0.00061 – 0.00076	**<0.001**	0.00046	0.00037 – 0.00054	**<0.001**	0.00056	0.00048 – 0.00064	**<0.001**
LOC × Stage [STR]	0.00095	-0.00417 – 0.00607	0.716	-0.00058	-0.00663 – 0.00547	0.851	0.00253	-0.00267 – 0.00774	0.340
LOC × Stage [LTR]	-0.00128	-0.00640 – 0.00384	0.624	0.00579	-0.00026 – 0.01184	0.061	0.00193	-0.00328 – 0.00713	0.468
LOC × Group [E]	-0.00735	-0.01815 – 0.00346	0.183	0.00456	-0.00968 – 0.01881	0.530	-0.00139	-0.00930 – 0.00653	0.731
Stage [STR] × Group [E]	-0.00513	-0.00734 – -0.00292	**<0.001**	-0.00116	-0.00377 – 0.00145	0.383	-0.00192	-0.00417 – 0.00032	0.093
Stage [LTR] × Group [E]	-0.00262	-0.00483 – -0.00041	**0.020**	0.00111	-0.00150 – 0.00372	0.403	-0.00119	-0.00343 – 0.00105	0.299
(LOC × Stage [STR]) × Group [E]	0.00405	-0.00239 – 0.01049	0.218	0.00373	-0.00388 – 0.01133	0.337	-0.00037	-0.00691 – 0.00618	0.912
(LOC × Stage [LTR]) × Group [E]	0.00991	0.00346 – 0.01635	**0.003**	-0.00253	-0.01014 – 0.00507	0.514	0.00389	-0.00265 – 0.01044	0.244
Random Effects									
σ^2	0.00023			0.00033			0.00024		
τ_{00}	0.00003_{ID}			0.00005_{ID}			0.00001_{ID}		
ICC	0.10367			0.13069			0.04596		
N	40_{ID}			40_{ID}			40_{ID}		
Observations	4800			4800			4800		
Marginal R^2 / Conditional R^2	0.072 / 0.168			0.039 / 0.165			0.047 / 0.091		
AIC	-26202.010			-24601.369			-26079.198		

TABLE XLI: Control Group as reference.

	Main Task EeStd			Target Transfer EeStd			Dynamics Transfer EeStd		
Predictors	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*
(Intercept)	0.01656	0.01388 – 0.01923	**<0.001**	0.02097	0.01749 – 0.02446	**<0.001**	0.01906	0.01702 – 0.02111	**<0.001**
LOC	-0.00400	-0.01055 – 0.00255	0.231	0.00157	-0.00706 – 0.01021	0.721	-0.00213	-0.00693 – 0.00267	0.384
Stage [STR]	-0.00153	-0.00304 – -0.00001	**0.048**	0.00328	0.00149 – 0.00506	**<0.001**	0.00083	-0.00071 – 0.00237	0.289
Stage [LTR]	0.00060	-0.00092 – 0.00211	0.439	0.00525	0.00347 – 0.00704	**<0.001**	0.00176	0.00022 – 0.00330	**0.025**
Group [C]	-0.00267	-0.00637 – 0.00103	0.158	-0.00027	-0.00516 – 0.00461	0.913	-0.00076	-0.00347 – 0.00196	0.585
sIndex	0.00248	0.00162 – 0.00335	**<0.001**	0.00282	0.00180 – 0.00385	**<0.001**	-0.00045	-0.00133 – 0.00043	0.314
wIndex	0.00068	0.00061 – 0.00076	**<0.001**	0.00046	0.00037 – 0.00054	**<0.001**	0.00056	0.00048 – 0.00064	**<0.001**
LOC × Stage [STR]	0.00500	0.00109 – 0.00890	**0.012**	0.00315	-0.00147 – 0.00776	0.181	0.00216	-0.00180 – 0.00613	0.285
LOC × Stage [LTR]	0.00863	0.00472 – 0.01253	**<0.001**	0.00325	-0.00136 – 0.00786	0.167	0.00582	0.00185 – 0.00979	**0.004**
LOC × Group [C]	0.00735	-0.00346 – 0.01815	0.183	-0.00456	-0.01881 – 0.00968	0.530	0.00139	-0.00653 – 0.00930	0.731
Stage [STR] × Group [C]	0.00513	0.00292 – 0.00734	**<0.001**	0.00116	-0.00145 – 0.00377	0.383	0.00192	-0.00032 – 0.00417	0.093
Stage [LTR] × Group [C]	0.00262	0.00041 – 0.00483	**0.020**	-0.00111	-0.00372 – 0.00150	0.403	0.00119	-0.00105 – 0.00343	0.299
(LOC × Stage [STR]) × Group [C]	-0.00405	-0.01049 – 0.00239	0.218	-0.00373	-0.01133 – 0.00388	0.337	0.00037	-0.00618 – 0.00691	0.912
(LOC × Stage [LTR]) × Group [C]	-0.00991	-0.01635 – -0.00346	**0.003**	0.00253	-0.00507 – 0.01014	0.514	-0.00389	-0.01044 – 0.00265	0.244
Random Effects									
σ^2	0.00023			0.00033			0.00024		
τ_{00}	0.00003_{ID}			0.00005_{ID}			0.00001_{ID}		
ICC	0.10367			0.13069			0.04596		
N	40_{ID}			40_{ID}			40_{ID}		
Observations	4800			4800			4800		
Marginal R^2 / Conditional R^2	0.072 / 0.168			0.039 / 0.165			0.047 / 0.091		
AIC	-26202.010			-24601.369			-26079.198		

TABLE XLII: Experimental Group as reference.

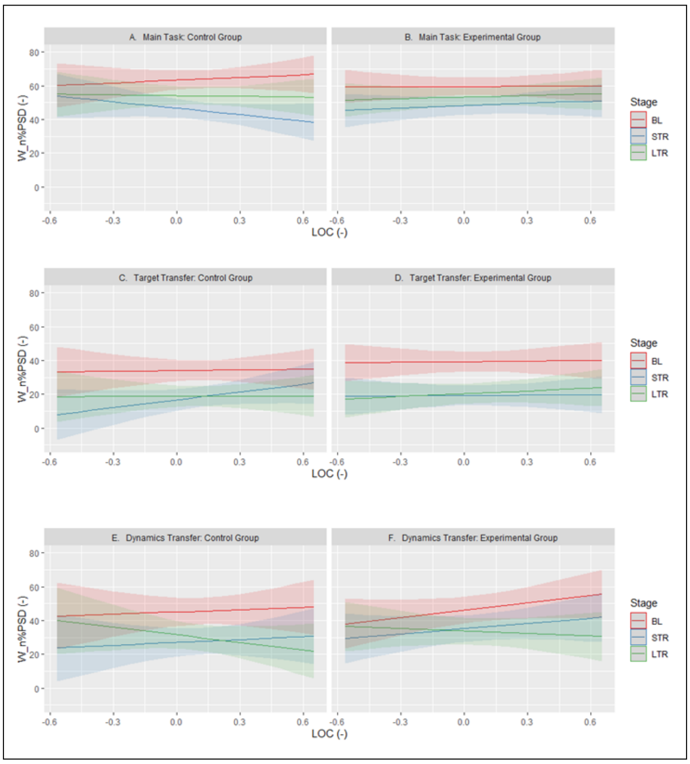

Fig. 35: Power Spectral Density around the Natural Frequency regression lines of the $LOC * Stage * Group$ term during Assessment Tests, shaded with their 95% confidence interval. Equation 7 is used with $\omega_N\%PSD$ as dependent variable (see F), and without the $wIndex$ term, as the metric is calculated at Set level. Each row shows a different Pendulum Task: **(A-B)** the Main Task, **(C-D)** the Target Transfer and **(E-F)** the Dynamics Transfer, with the first column the Control Group and the second column the Experimental Group.

Regression Results of Power Spectral Density percentage around Natural Frequency during Assessment Tests (Equation 7 with $\omega_N\%PSD$ as dependent variable). Not FDR Corrected.

	Main Task W_n%PSD			Target Transfer W_n%PSD			Dynamics Transfer W_n%PSD		
Predictors	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*
(Intercept)	68.10553	62.18393 – 74.02714	**<0.001**	32.71350	26.09087 – 39.33612	**<0.001**	47.08241	38.47201 – 55.69280	**<0.001**
LOC	5.41013	-12.59730 – 23.41757	0.554	1.39470	-18.78196 – 21.57137	0.892	4.25047	-22.40594 – 30.90687	0.754
Stage [STR]	-16.65917	-23.16221 – -10.15612	**<0.001**	-17.34959	-24.47986 – -10.21932	**<0.001**	-18.05208	-25.49892 – -10.60524	**<0.001**
Stage [LTR]	-9.13755	-15.64060 – -2.63451	**0.006**	-15.19665	-22.32692 – -8.06638	**<0.001**	-13.53308	-20.97992 – -6.08624	**<0.001**
Group [E]	-3.73347	-11.49767 – 4.03072	0.344	5.29599	-3.40349 – 13.99548	0.232	1.15851	-10.33482 – 12.65184	0.843
sIndex	-9.45149	-12.95449 – -5.94849	**<0.001**	2.66554	-1.17532 – 6.50641	0.173	-3.94871	-7.96010 – 0.06269	0.054
LOC × Stage [STR]	-18.25044	-38.95230 – 2.45143	0.084	13.97712	-8.72146 – 36.67569	0.226	1.42699	-22.27936 – 25.13334	0.906
LOC × Stage [LTR]	-6.94816	-27.65003 – 13.75370	0.509	-1.02468	-23.72325 – 21.67390	0.929	-18.93606	-42.64241 – 4.77029	0.117
LOC × Group [E]	-5.17620	-27.81942 – 17.46702	0.653	-0.36588	-25.73677 – 25.00502	0.977	10.19231	-23.32645 – 43.71107	0.550
Stage [STR] × Group [E]	5.15446	-3.77148 – 14.08039	0.256	-2.69390	-12.48075 – 7.09295	0.588	6.98443	-3.23694 – 17.20580	0.179
Stage [LTR] × Group [E]	2.81869	-6.10725 – 11.74462	0.534	-3.77710	-13.56395 – 6.00975	0.448	1.04313	-9.17824 – 11.26449	0.841
(LOC × Stage [STR]) × Group [E]	22.70225	-3.32905 – 48.73354	0.087	-14.22157	-42.76361 – 14.32047	0.327	-5.50337	-35.31261 – 24.30588	0.716
(LOC × Stage [LTR]) × Group [E]	9.74061	-16.29068 – 35.77191	0.462	5.52054	-23.02150 – 34.06257	0.703	-0.29975	-30.10899 – 29.50950	0.984
Random Effects									
σ^2	189.60543			227.94447			248.63435		
τ_{00}	48.65888 $_{ID}$			66.13481 $_{ID}$			190.04845 $_{ID}$		
ICC	0.20422			0.22489			0.43323		
N	40 $_{ID}$			40 $_{ID}$			40 $_{ID}$		
Observations	240			240			240		
Marginal R^2 / Conditional R^2	0.217 / 0.377			0.207 / 0.385			0.138 / 0.511		
AIC	1933.617			1978.163			2023.519		

TABLE XLIII: Control Group as reference.

	Main Task W_n%PSD			Target Transfer W_n%PSD			Dynamics Transfer W_n%PSD		
Predictors	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*
(Intercept)	64.37206	58.77271 – 69.97141	**<0.001**	38.00949	31.74865 – 44.27033	**<0.001**	48.24092	40.11667 – 56.36516	**<0.001**
LOC	0.23394	-13.49369 – 13.96156	0.973	1.02883	-14.35247 – 16.41012	0.895	14.44278	-5.87823 – 34.76378	0.163
Stage [STR]	-11.50471	-17.61885 – -5.39057	**<0.001**	-20.04349	-26.74735 – -13.33964	**<0.001**	-11.06765	-18.06914 – -4.06616	**0.002**
Stage [LTR]	-6.31886	-12.43301 – -0.20472	**0.043**	-18.97375	-25.67760 – -12.26989	**<0.001**	-12.48995	-19.49144 – -5.48846	**0.001**
Group [C]	3.73347	-4.03072 – 11.49767	0.344	-5.29599	-13.99548 – 3.40349	0.232	-1.15851	-12.65184 – 10.33482	0.843
sIndex	-9.45149	-12.95449 – -5.94849	**<0.001**	2.66554	-1.17532 – 6.50641	0.173	-3.94871	-7.96010 – 0.06269	0.054
LOC × Stage [STR]	4.45181	-11.32986 – 20.23349	0.579	-0.24445	-17.54828 – 17.05938	0.978	-4.07638	-22.14846 – 13.99571	0.657
LOC × Stage [LTR]	2.79245	-12.98922 – 18.57412	0.728	4.49586	-12.80796 – 21.79969	0.609	-19.23580	-37.30789 – -1.16372	**0.037**
LOC × Group [C]	5.17620	-17.46702 – 27.81942	0.653	0.36588	-25.00502 – 25.73677	0.977	-10.19231	-43.71107 – 23.32645	0.550
Stage [STR] × Group [C]	-5.15446	-14.08039 – 3.77148	0.256	2.69390	-7.09295 – 12.48075	0.588	-6.98443	-17.20580 – 3.23694	0.179
Stage [LTR] × Group [C]	-2.81869	-11.74462 – 6.10725	0.534	3.77710	-6.00975 – 13.56395	0.448	-1.04313	-11.26449 – 9.17824	0.841
(LOC × Stage [STR]) × Group [C]	-22.70225	-48.73354 – 3.32905	0.087	14.22157	-14.32047 – 42.76361	0.327	5.50337	-24.30588 – 35.31261	0.716
(LOC × Stage [LTR]) × Group [C]	-9.74061	-35.77191 – 16.29068	0.462	-5.52054	-34.06257 – 23.02150	0.703	0.29975	-29.50950 – 30.10899	0.984
Random Effects									
σ^2	189.60543			227.94447			248.63435		
τ_{00}	48.65888 $_{ID}$			66.13481 $_{ID}$			190.04845 $_{ID}$		
ICC	0.20422			0.22489			0.43323		
N	40 $_{ID}$			40 $_{ID}$			40 $_{ID}$		
Observations	240			240			240		
Marginal R^2 / Conditional R^2	0.217 / 0.377			0.207 / 0.385			0.138 / 0.511		
AIC	1933.617			1978.163			2023.519		

TABLE XLIV: Experimental Group as reference.